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International Thermonuclear Experimental Reactor (ITER) Neutral Beam Design - Summary Report for FY 1990

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CONTENTS

1 - INTRODUCTION

Grumman was contracted by Lawrence Livermore National Laboratory (LLNL) to support Lawrence Berkeley Laboratory (LBL) in their design of the International Thermonuclear Experimental Reactor (ITER) neutral beam line. The effort undertaken was documented for LLNL and LBL in monthly notes starting in March 1990 when the contract was negotiated. This report summarizes the activities.

Operating conditions and configurations specified for the neutral beam line in 1990 were similar to the 1989 configuration. Updates and changes were received in the form of FAX transmittals from LBL.

2 - BEAM LINE DEFINITION

The effort undertaken in FY 1990 principally comprised an evaluation of the beam line components downstream of the accelerator as they were affected by the changes defined by LBL compared to the previous year's configuration. The key changes were:

* Increased current output per beamlet (channel)
* Use of an electromagnetic deflector in lieu of an electrostatic deflector
* Requirement to design for commissioning (inactive neutralizer)
* Magnetic instead of mechanical steering of the accelerated current

The current per beamlet change affected the neutralizer design (wider entrance as a result of a wider beam), and increased current density concentration on the ion dump. Choice of an electrostatic deflector effected a shorter beam dump. The commissioning imposed a requirement to design one ion dump to intercept the total current from a source array, and the use of magnetic steering at the neutralizer entrance allowed the height of its entry slots to be reduced.

The FY 1989 report listed nomenclature used by the US team, because a standard set has not been defined for the international participants. The list is shown in Figure 1, and includes terms adopted since last year.

The changes on configuration provided by LBL, which affected the downstream components are summarized in Figure 2.

An alternative pumping arrangement in which the beam line pumps are appended, was assessed. The analysis is presented in Appendix A.

3 - DISCUSSION

The components downstream of the accelerator exit included in the evaluation are the neutralizer, ion deflector/dump, drift duct, vacuum pumping system, and the cryogenic system. The internal dimensions of the neutralizer and the ion dump, which interact with the current, are sized by the locus of the skim angles of the beams in the horizontal and vertical directions, and by the ion trajectories downstream of the neutralizer. The arrangement of those components is shown in Figure 3. The ion dump plates are positioned to intercept all deflected ions. The gap between the neutralizer exit and the ion dump entrance is occupied by a portion of the deflecting magnet, which was not analyzed fully in the effort reported here.

The geometry of the radiation shielding incorporated in the baseline neutralizer was not included in the trade studies of the neutralizer, so that the full effect of the variables (baffles, side wall positions, etc.) could be assessed.

3.1 ION DUMP

Two important requirement changes from 1989 affected the design of the ion dump. These were requirements to:

- Design for beam line commissioning
- Design for one ampere beamlets (was 0.13A)

The consequence of these conditions is that the comparable maximum heat flux to which the dump can be exposed is significantly increased.

The purpose of the neutral particle beam ion dump is to absorb the energy of those un-neutralized particles in the beam after it has passed through the neutralizer. The dump is exposed to two operating conditions which are steady state current drive operation and beam line commissioning. During commissioning of the beam, the neutralizer is not in operation and the entire negative ion flux generated in the source/accelerator strike one of the two dump plates on either side of a beam line array (two arrays per module). The commissioning dump plate is designed for steady state operation to accommodate the entire commissioning heat load. The dump plate on the opposite side of the beam line array can be designed for the operational heat load only, which is 20% of the commissioning values (Figure 4). The recommended design is very flexible in that it can accommodate the maximum heat load at any location on the dump surface and thus can be used during commissioning at all operating conditions. The heat fluxes used are given in Ref. 1. Three ion dump designs were considered: One using horizontal venetian blinds (baseline design): one using closely spaced vertical swirl tubes (alternate); and one using reverse vertical venetian blinds (discarded).

The beam source design consists of eight channels per array mounted vertically. Each channel flux streams out of the neutralizer highly compacted and separated vertically (22 cm) one from another. As a result the beam line ion flux flowing to the ion dump is confined to localized high current density areas, one for each channel. Figure 5 is a plot of heat flux of the ions crossing the plane of the ion dump along a vertical line at the beam line location of maximum heating values; that is 215 cm downstream from the neutralizer exit (Ref. 1 data). Shown on the curve is the data for the four channels located above the beam centerline. The four peak values (1.93 kW/sq cm or 19.3 MW/sq m) are for the ions originating at the center of the channels.

Figure 6 is a plot of heat flux of the ions crossing the plane of the dump along a line in the beam direction at the location of a channel centerline (Ref. 1 data). The peak value of 1.93 kw/sq cm or 19.3 MW/sq m is again shown at 215 cm downstream from the neutralizer exit.

3.1.1 Baseline Ion Dump

Figure 7 shows a pictorial trimetric view of the baselined horizontal venetian blind ion dump. Plates are placed along the side of the dump at an angle (13^{o}) with respect to the horizontal to reduce the heat flux on them. Swirl tubes are placed at the plate leading edges to protect the edges from the oncoming high flux density. Coolant channels in the plate run normal to the beam line and are connected to coolant headers at the rear of the plates. Each plate coolant inlet and outlet header is connected to a common inlet and outlet header at the upstream end of the dump. The swirl tubes have a separate coolant system because the coolant flow conditions are different. The swirl tubes are connected to a common inlet header located at the upstream end of the dump. Their outlet header is located at the downstream end of the dump.

Figure 8 shows an end view of the horizontal venetian blind commissioning ion dump (Beam flow into the paper). There are 41 venetian blind plates spaced five cm apart and each is 22 cm long. At a 13 degree angle the region behind the plates is opaque to the direct beam flow. Swirl tubes are shown at the leading edges of the plates.

Figure 9 shows the results of a study of the stresses, front face temperature and frontal heat flux as a function of angle with the horizontal of a venetian blind ZrCu flat plate with milled coolant channels. The study is made for the baseline coolant and coolant channel conditions. The water coolant flows through the channels at 9 m/s with inlet and outlet temperatures of 30 and 98 (maximum) degrees C respectively. The front wall thickness is 0.3 cm and the channel width and depth are 0.6 and 0.2 cm respectively. The total plate thickness is 6.8 mm, that is, the same as the outside diameter of the baseline swirl tube which protects the plate leading edge.

The boiler code stress is a fraction of the yield and creep rupture stresses of the material. It is a conservative value typically used in design as the allowable stress for steady state heating conditions. The combined stress, the sum of the thermal and pressure stresses is plotted against plate angle. The thermal stress, a result of the temperature gradient across the front wall, is a major fraction of the maximum combined stress in the material. The maximum allowed heat flux (4.3 MW/sq m) occurs at the point where the combined stress is equal to the boiler code stress. For the assumed geometry this value is the maximum that a simple cooled flat plate can take. Note that as the ITER device trends away from being a steady state device, then fatigue limitations of the dump must be considered.

The swirl tube, proposed as a means of protecting the dump plates' leading edges, is an externally heated water cooled tube with an internally twisted tape that forces the flowing coolant to swirl in a helical pattern. The swirling action scrubs the internal boundary layer from the tube surface and increases the heat transfer rate into the coolant. This device developed during the late 50s, can withstand fluxes in excess of 20 MW/sq m (Ref. 2,3). State of the art swirl tubes however are relatively short (maximum lengths of about 25 cm), hence their applications are limited to narrow heat flux regimes.

Discussions with W. Gambill (Ref. 4) indicate that it may be possible to design a swirl tube of length greater than the 25 cm maximum reported in Ref. 2. The tube length could be the full length or height of the ion dump, about 2 m. One could use a tube configuration that has already been tested for a certain heating flux and heating load, increase the length to that required and use it at a flux and load equal to or less than that tested.

Burnout of a swirl tube typically occurs at the coolant outlet end where residual steam vapor forms at this point of hottest coolant. This formation reduces the coolant film coefficient and drives the metal surface temperature of the tube above the melting point. However, if the operating conditions of the lengthened swirl tube are such that the local average temperature of the coolant is everywhere below the flash point, and if the above mentioned heating conditions are satisfied, then it is felt that the tube will avoid burnout. A test program would be required to verify this conclusion.

The specifications of three swirl tubes considered for use in the ion dump are given in Figure 10 (Ref. 2).

Figure 11 is a plot of the required coolant pumping power as a function of extended length for the three swirl tubes covered in Figure 10. The swirl tube of test number 28 (Ref. 2) was chosen as the reference design because it required the lowest pumping power and has an outside diameter large enough to shield the venetian blind plate. The design pumping power for the 41 swirl tubes is 80 kW and their lengths are 208 cm.

The specifications and performance of the venetian blind plates and the leading edge swirl tubes are presented in Figures 12 and 13. The vertical magnetic field that turns the ions out of the main beam line into the dumps is generated by the current in a saddle coil. The coil conductors along both sides of the beam line could be separate wires placed at he rear of the venetian blind plates or they could be the venetian blind plates themselves. The magnet extends forward to the neutralizer to effect ion deflection from that axial location. The current requirement of the field is 20000 A turns requiring 7 kW. The coil would weigh 400 kg.

3.1.2 Other Ion Dump Designs

Alternate designs for the commissioning ion dump that could accommodate the maximum heat flux at any location on the surface were considered. One was an array of closely spaced vertical swirl tubes covering the entire height and required length of the dump. This full surface "ladder" design makes use of the swirl tube of test case 28 noted above (Ref. 2). The tubes are spaced so that the region behind the dump is opaque to the direct beam flux. Figure 14 shows a pictorial trimetric view of the full surface ladder ion dump with coolant headers running in the beam direction at the top and bottom of the dump. The performance and specifications of the swirl tubes that are different than those presented above for the venetian blind design are given in Figure 14.

A second alternate makes use of a reverse vertical venetian blind dump. Each plate shields the leading edge of the one immediately downstream. The plates are oriented at a very shallow angle relative to the incoming flow in order to increase the impingement area by a factor of about five to reduce the heat flux to the plate to the maximum allowed value of 4.3 MW/sq m. However, this requirement lengthens the ion dump from about 2 to 10 m. The use of this dump would be inconsistent with the overall plan to make the neutral particle beam line as compact as possible, therefore the design was discarded.

3.1.3 Considerations of Dump Life

The sputtering of the normal operating dump was checked for the operating conditions of Ref. 1. For a flat copper plate along the edge of the beam with an allowed sputtering thickness of 0.5 cm, the plate lifetime at the point of maximum heating flux is 8 full power years. The commissioning dump venetian blind plates will be subjected to slightly greater fluxes during commissioning but much lower fluxes during normal operating conditions. Sputtering of the plates should not be an issue during commissioning since the actual commissioning time is a small fraction of the total operating time. The present swirl tube design has a wall thickness of 1 mm. Future design will require additional wall thicknesses to accommodate a few full power years of sputtering (one year service is assumed for maintenance evaluation (Section 3.5)). Further investigation of this sputtering issue should be made.

3.2 NEUTRALIZER AND MODULE GAS FLOW ANALYSIS

The gas flow distribution in the beam line, determined from 3-D modeling, was calculated to allow sizing of the cryopumps located in the accelerator exit cavity and the ion dump cavity. The effect of gas flow exiting the ion source cavities was not included in the study; these data were provided by LBL in Ref. 3.2 (FAX of 8-10-90) and were included in the pumping analysis (Section 3.3).

3.2.1 Neutralizer Analysis

With the exception of the ion source, the neutralizer is the main source of gas flow in the beam line; the other source is the plasma.

The neutralizer geometry used for gas flow and distribution analysis was affected by the beamlet sizes, placement and divergence (FAX of 3-26-90) and by the neutralizer's position with respect to the accelerator exit (FAX of May 8 1990). These conditions, coupled with the basic neutralizer design constraints from FY 1989, defined a design envelope. Other modifications allowed the length of the entry portion of the neutralizer to be increased from 50 cm to 100 cm to extend it upstream between the beam vertical steering system ($\pm$15 mrad vertically only). The radiation shield which affects the neutralizer configuration was omitted from the analysis, so that that the traded variables could be assessed fully. The presence of the shield constrains the walls of the neutralizer to follow the locus of the beam skim angle. The analysis showed that such an arrangement reduces the effective line density integral through the neutralizer.

A series of runs was undertaken to benchmark the line density integral for a neutralizer with exit and entry slots of sufficient width to accommodate the beam horizontal skim angle. The line density integral (N/No dl) in Figures 15 to 19 is defined as the integral of the particle count N along the neutralizer length (l) ratioed to the number of particles (No) introduced at the injection point entrance. Line density integral was used as the figure of merit for assessing alternative configurations. The first series of runs resulted in line density integrals drastically lower than achieved last year. In an attempt to raise the line density integral, blockages to retard the neutralizer gas flow were added between the line-of-sight of the beamlets at the entrance and exit of the neutralizer steering section. These blockages were placed so as not to restrict beam vertical (± 15 mrad) movement, but solely to direct the neutralized gas preferentially toward the ion dump compartment.

Figure 15 shows the significant benefit of the blockage, and also shows the effect of including baffles in the neutralizer box.

Increasing the number of baffles directly increased the line density integral Carrying this to the extreme, an infinite number of baffles would be seem the best. This condition, which exemplifies the constraint imposed by the radiation shield, was investigated by creating a geometry file in which the side walls were perfectly aligned with the beam divergence angle. Figure 15 shows that this case effected lower performance. Therefore, 15 baffles was selected as a baseline.

The effect of gas injection location on line density was evaluated. For this study the zero percent injection was taken to be the exit from the steering (entry) section of the neutralizer, and the 100% location was the exit from the neutralizer. Figure 16 clearly show that the benefit of injection between 12.5 and 25% is independent of the number of baffles. Therefore a choice of 25% was selected for the baseline.

The effect of widening the neutralizer section was examined. Figure 17 shows the results of the first two parts of this study i.e., width and number of barriers. This figure clearly shows a definite benefit gained by increasing the width of the neutralizer. For the case of 15 barriers, roughly doubling the width from 14.4 cm to 30 cm, resulted in a 60 % increase in line density integral. The same dramatic increase was not recorded however for the 10 barrier comparison shown in Figure 17. For this case only a 20 % increase was indicated. However, in each the results favored a wider neutralizer. The other criterion for performance comparison is the amount of neutralizer gas load directed toward the ion dump compartment by each configuration. In order to try to keep the conductances approximately the same, when the 30 cm wide neutralizer model was generated another set of barriers was added at the exit to maintain a minimum exit area. The legend on each figure indicates this. So the number of baffles for a wide neutralizer model is incremented by one, i.e. 15+1. Figure 18 reveals that adding the barriers to the exit effectively maintains the low gas load to the ion dump compartment. This is highly desirable.

From the Berkeley data available on the clearance requirements of each beam line component a preliminary estimate was made which indicated that the the neutralizer main body could be widened to a maximum of 60 cm. This model was constructed along the same lines as the 30 cm wide model. The barriers extend from the side walls, each of which is now 30 cm from the beamlet centerline, to beam skim. Also there is an additional set of barriers at the exit to maintain the exit areas constant for all the models. Figure 19 clearly indicates that increasing width has the positive effect of increasing line integral. Comparing the results at the maximum line integral location, injection at 25%, indicates a 154% increase in line integral. As before, the percent flow aft to the ion dump compartment was also examined. Figure 20 shows that there is no significant differences in gas load between different width configurations. This is another indication that the neutralizer width should be allowed to grow.

The results of the last study, injecting neutralizer gas at the beam skim as opposed to at the neutralizer walls, is also on Figures 19 & 20. Coupled with this study was a desire to increase the number of particles used in the analysis. All the runs to date used for comparison were made with 20,000 particles. This is consistent with the approach used last year for this analysis. However, at the indicated maximum point for the 60 cm wide, 15+1 baffles configuration a 100,000 particle trajectory run was undertaken. If any statistical inconsistencies were contained in the prior runs this should have brought them out. The results are barely distinguishable from the comparable case where the gas was let in from the neutralizer walls. Subsequently, the injection at skim study was abandoned, and the concern over using 20,000 particles for comparison purposes was satisfied.

Reviewing the entire neutralizer investigation to date reveals several strong points in favor of certain design aspects. These are, in order of impact on line density integral, neutralizer width, number of barriers, and neutralizer gas injection point. The study reveals that future concepts for gas neutralizers should be designed to have a maximum width in the neutralizer compartment, 15 barriers, minimum exit areas, and an injection point of neutralizer gas between 25 to 37.5% in the neutralization chamber. This combination of design variables would yield the highest line density integral and an acceptable gas load to the ion dump compartment. Figure 21 represents the best configuration examined to date. It is the 60 cm wide, 15+1 barrier model with gas injection from the wall at 25% in the neutralizer compartment. It will be used as the baseline for all continuing work.

3.2.2 Accelerator Model

Figure 22 shows the model used for analysis of this location. The model was based on eight beamlets, three cryopumps, an interface with the neutralizer (an exit for this model), wall dimensions and the necessary support structure. Symmetry allows half a beam line to be modeled. All dimensions were taken from LBL FAX transmittals. Following the same methods employed in the neutralizer analysis, the model was used to obtain number density ratios at certain locations within the model. Figure 23 shows the resultant pressure distribution lengthwise (beam direction) and vertically (perpendicular to the beam in the plane of the pump), for the accelerator cryopump surface. This figure shows no significant pressure imbalance on the face. This result projects an even pumping speed for the entire area.

3.2.3 Ion Dump Model

Figure 24 is a sketch of the model used for Monte Carlo investigation of the ion dump compartment. Also contained in the figure is a blow up of the swirl tube (venetian blind) ion dump. Venetian blind dumps were placed at both sides of the beam: however the inboard (non-commissioning) dump will probably be greatly simplified in subsequent design studies. This model encompasses all the geometry between the exit of the neutralizer and the isolation valve. Again symmetry of the beam line requires only half of the module to be depicted. All compartment dimensions were taken from the recent set of LBL FAX transmittals. Figure 25 contains the resultant pressure distribution for this model across the cryosurface. As noted on the figure, this distribution is referenced to an accelerator exit pressure of 9.8E-05 Torr. Although the distribution of pump pressure across the face is not as even as for the accelerator distribution, the pump's capability is acceptable.

3.2.4 Drift Duct Model

Figure 26 contains a sketch of the model used for evaluation of the common drift duct for one beam line. The model extends from the isolation valve to the plasma. The barriers modeled in FY 89 are deleted since all bioshielding will be done upstream at the neutralizer entrance.

An analysis was undertaken to see what impact the barriers would have on the beam line pressure. Figure 26 had barriers installed at approximately the same locations as the FY 1989 drift duct had. The barriers last year created localized increased pressure spikes which impacted the component efficiency. This same result was noted again this year. The overall beam line pressure profile was not changed (neglecting the localized barrier effect) when comparing the GRAVE (Grumman Analysis of Vacuum Enclosures) runs with, and without, barriers. The resultant final pressure at the torus was unchanged. Therefore, the drift duct without barriers is recommended. This model completes the GRAVE component analysis of the current design.

3.2.5 Gas load calculation

The GRAVE models were used to determine the gas loading of the current module design. The major gas sources are the neutralizer, the source/accelerator, and to a lesser degree the plasma itself. The transmission probabilities calculated by the GRAVE code for each module segment, along with the information from the calculated number density, allows the gas loads for each cryosurface to be calculated. The entire beam line system was pieced together.

The calculations use the source gas load, the accelerator exit pressure, the plasma edge pressure, and the ideal line density integral as input data. The values used for these key parameters are 25.6 Torr-l/s (per beam line), 9.8e-05 Torr (source), 1e-06 Torr (plasma), and 1.7e+16 cm^{-2} (FY 1989 value from P. Purgalis for 1.3 MeV D^o beam). Figure 27 shows the resultant pressure distribution along a beam line from accelerator to plasma. The total gas loading, and subsequent cryopanel sizing is summarized (per beam line values) in section 3.3.

3.3 VACUUM SYSTEM

The function of the vacuum system during cw operation is to maintain an acceptable line density from the exit of the accelerator to the plasma. The major gas loads issue from the ion sources and the gas cell neutralizer, lesser loads from neutralized ions in the ion dump and from re-ionized particles born in the ion dump and drift duct.

3.3.1 Pump Sizing

The estimated gas loads per beam line in Torr-l/s D_2 are:

Source	25.6
Neutralizer gas flow toward accelerator	4.24
Neutralizer gas flow toward ion dump	10.28
Flow to plasma	*
Dumped ions	*
Reionized neutrals - ion dump	*
- drift duct	*
Total	40.12

* negligible for pump sizing

The pressure in the beam line at the accelerator exit is 9.8e-05 Torr. With this pressure set, 3-D Monte Carlo analysis using GRAVE code reveals that the resulting beam line pressure at the exit of the neutralizer is 3.5e-04 Torr. Figure 27 depicts the indicated pressure distribution from the GRAVE analysis. This pressure distribution assures the beam loss through the dump compartment is less than 10% and the drift duct compartment loss is less than 3%. The GRAVE analysis also indicates cavity pressures in the two cryopump compartments of a beam line which are lower than beam line pressures because the cavities are behind beam line equipment. In the forward pump cavity the pressure is 5.1e-05 Torr, with a corresponding cavity pressure in the ion dump compartment of 1.45e-04 Torr. These pressures, in conjunction with the throughputs listed, determine the amount of extra capability each pumping station has. All pump sizing uses the specific pumping speed of a chevroned cryopump for D_2 = 7.9 liter/s/cm2.

The pumping arrangement at the accelerator exit comprises six cryopumps, Three on each side of the beam with two of these panels operating and one panel regenerating at any time. All of these pumps will have the capability to be regenerated individually. Each pumping panel is 125 cm wide by 250 cm high. This yields an effective pumping surface of 12.5 m^2. This pumping configuration provides 40% excess pumping capability.

There are four cryopumps at the ion dump location, two on each side with one operating and one being regenerated. Each panel is 125 cm wide by 300 cm high. These panels have 88% excess capability at the stated conditions. These pumps, like the upstream pumps are effectively in compartments adjacent to the beam line subsystems and thus operate at a pressure lower than that stated for the beam line.

To summarize the vacuum system:

Compartment	Accelerator	Ion dump
Pump height (m)	2.5*	3.0
Pump width (m)	1.25*	1.25
Number operating	4	2
Number regenerating	2	2
Beam pressure (Torr)	9.8e-05	3.5e-05
Cavity pressure (Torr)	5.1e-05	1.45e-04
Gas load (Torr-l/s)	29.84	10.28
Pumping speed (m^3/s)	584.4	70.9
Required operating area (m^2)	7.39	0.9
Available operating area (m^2)	12.5	7.5

*Purgalis memo of 8/9/90 changed these dimensions, but the area was effectively unchanged.

3.3.2 Cryopump Heat Load Analysis

The cryopump heat load analysis is based on the the model shown in Figure 28. All cryopumps are configured the same. The two sided helium panel faces a chevron on one side and a closed shield on the other, all LN-cooled to 80K. The composite emissivity of this is 0.31. This correlates into a load on the helium of 2.53 W for an accelerator cryopump, and a load of 3.02W per ion dump compartment cryopump. This translates into a total accelerator load of 10.15 W (four operating pumps), and a total load of 6.05 W for the ion dump cryopumps (two operating). In order to account for the panel supports, feed and vent lines, and finally any nuclear load an extra 20% margin will be figured into the final loads on the helium. The other heat load, directed at the nitrogen, is a composite of the load placed on the chevrons, and the exterior of each individual pump. In the accelerator cavity the chevrons are opposite a 300K wall with an $\varepsilon = 1$. This translates into a heat load of 285.7 W. The exterior shielding of the cryopump is estimated to have $\varepsilon = 0.2$. The resultant heat load is 303.52 W. Taking these per pump values and multiplying by the number of cryopumps , and allowing an extra twenty percent to handle installation contingencies listed before indicates that the nitrogen load for the accelerator cavity cryopumps is 4242.72 W (or 98.5246 l/hr consumption). The corresponding ion dump cryopump figures are: Heat load on chevron per pump 342.89 W, heat load on shield per pump 353.05 W, and total load with contingency is 3340.53 W (or 77.57 l/hr consumption).

3.3.3 Pumping Panel Helium Temperature

The pumping panel temperature affects the pumping effectiveness of a condensing cryopump. Since the cryopumps are to be liquid filled, a small analysis is described to obtain a maximum operating cryopanel temperature. The following short analysis (after L.Pittenger, UCRL-78501, 1976) shows selection of a helium-cooled pump for these applications. Effective pumping speed S_s as a function of panel temperature T_s follows the relation:

$$s_s = 36.4 \times \left(\frac{T}{M}\right)^{0.5} \times \left(\left(\frac{1}{t}\right) + \left(\frac{1}{C_{eff}}\right) - 1\right)^{-1} \quad \text{in} \quad \frac{m^3}{s\ m^2}$$

where

t chevron transmissivity (0.25)

T pumped gas temperature (300 K)

M molecular weight (4)

C_{eff} effective sticking probability of gas on condensing surface

$$C_{eff} = c\left(1 - \left(\frac{T_2}{T_s}\right)^{0.5}\right) \times \left(\frac{P_{vap}}{P_p}\right)$$

c	sticking coefficient on cryopanel (1.0)
T_2	gas temperature behind chevron
T_s	shield temperature
P_{vap}	vapor pressure corresponding to T_s
P_p	pressure behind chevron (P_{cav} x t = 3.62e-05 Torr)

(P_{cav} at ion dump = 1.45e-04 Torr)

Ts (K)	Pvap (Torr)	Ss (l/s-cm2)
4.2	1e-11	7.8807
5	4e-09	7.8790
6	1e-06	7.4298

From the above results the maximum recommended cryopump panel operating temperature = 5K.

3.3.4 Regeneration Analysis

Since cryopumps being used in this manner are limited by several factors, an analysis of the time between regeneration is included for completeness. The limiting factor in this application is estimated to be the safety limit for hydrogen buildup. A partial pressure limit of 12 Torr for D_2 is acceptable in the event of a sudden inadvertent air ingress. The method used here will be to determine the free volume in the beam line, then to use the acceptable partial pressure requirement stated to arrive at a total D_2 accumulation, then finally to estimate this build up from the throughput per beam line. This calculation indicates that the time to reach the limit is achieved in 9.89 hrs. In summary:

Vacuum tank volume (liters)	191640.0
Volume of beam line components +20% to cover installation lines (liters)	69000.0
Free Volume (liters)	122639.0
Resultant D_2 load before regeneration (Torr -l)	1471674.0
Throughput (Torr-l/s)	41.3
Time between regeneration (hrs)	9.89

For additional safety the regeneration interval will be reduced to 8 hrs. for the cryopump power required analysis. During each regeneration period two cryopumps in each of the accelerator and ion dump compartments will be serviced. Since at this time the cryopumps have no specific construction guidelines, for this analysis the pumps will be those described in Figure 28. All material will be considered to be aluminum, with a wall thickness of 0.318 cm (1/8" inch). The material specific heat at 20 K =0.01 j/g-K (Barron), and all panels will be cooled from 20 K to 4.2 K after regeneration. Also, the coolant driven from the panel will be by warm gas which will be recovered in a storage dewar. The analysis will include the power required to cycle the helium, aluminum, and a small contingency to cover installation hardware not direct stated. The results of the analysis are summarized:

Per pump type	Accelerator comp.	Ion Dump comp.
Contained Helium volume (l)	10.55	11.31
Energy of vaporization (j)	3637	3899
Mass of Aluminum (kg)	77.67	91.32
Per beam line (2 pumps each compartment)		
Avg. power for Helium venting(W)	0.252	0.270
Avg. power for aluminum cooling (W)	0.51	0.60
Totals	0.762	0.870

Total liquid Helium required per regeneration, per beam line = 18.5 liters

3.3.5 Pump Safety

The last item to be considered is cryopump safety. Cryopumps require venting capability in the event of a sudden increase in heat flux to the pump's helium coolant. This causes a transient buildup in pressure within the pump. FY 1989 contained an analysis to estimate the type of system necessary to maintain pump integrity during this type of situation. It is still valid for the FY 1990 vacuum system.

3.4 CRYOGENIC SYSTEM

The cryogenic system analysis provides a summary of cryogenic requirements for the 9 - module beam line system. Definition of the distribution system is unchanged from last year. The update presented here reflects response to comments made on last year's draft report.

The cryogenic system provides liquid nitrogen for thermal shielding of the liquid helium in the beam line cryopumps and storage dewars, and provides liquid helium for:

* Pump cool down prior to operation.
* Pump coolant during operation.
* Pump chill down during the regeneration procedure.
* Distribution and storage system thermal losses.

Although the first item will require a significant amount of coolant, it is not expected to size the cryogenic plant. The last three demands will determine liquefaction requirements. The time-averaged loads (all beam lines) at 4.2K, including pump operation, regeneration, distribution and storage with a 20% contingency are 427 W helium and 1891.1 l/hr nitrogen. The requirement for the refrigerator/liquefier and for the distribution system upstream of an interface at 10 m from the beam line cryogenic distribution manifold is not included.

A proposed helium distribution system for the beam line cryopumps is shown in Figure 29. A storage dewar mounted on the beam line supplies liquid helium to a pump of group of pumps. When the pump is ready for regeneration, the supply valve (No. 1) between the dewar and the pumping panel is closed, and ambient temperature gas is fed to the panel to expel the coolant. The expelled coolant is directed back to the dewar through valve No. 2 until the vented gas warms to 15 K, at which point it is diverted to the liquefaction unit. The panel is warmed to 20 K to dump the pumped deuterium from the pumping panel. The deuterium is rough pumped either from the beam line, if an entire beam line is isolated from the plasma chamber, or from a secondary chamber that is part of the cryopump (regenerable cryopump) and can be isolated from the beam line volume. The latter case, which allows continuous beam line operation, requires a more complex distribution system Figure 30 to allow sequential pump operation and regeneration.

The proposed ITER regeneration scheme captures the regenerated gas within the cryopump, thus avoiding the need to process extra gas with the tritium containing effluents from the beam box. Such a pump was developed and demonstrated by LLNL and Grumman (JVST A 6 (3), 1209, May 1988).

The sketches shown in Figures 30 and 31 provide the basis for estimation of cryogen requirements. Requirements for the cryopumps are described previously. All helium distribution lines are assumed to be 1 inch diameter. Liquid helium lines are vacuum jacketed and not LN traced or helium vapor cooled. Inclusion of the latter features would reduce heat input to the cryogen at the expense of complexity. The trade for TFTR found against inclusion of these features, but the economies for ITER would have to be determined.

The linear dimensions of the distribution lines were estimated last year and are tabulated below for reference. The location numbers refer to Figure 31.

Identification/Location	Length meters				
Line type:	LHe	Cold He	Warm He	GN	LN
Refrig/supply interface to ring manifold, 1-3	10.0	9.5	9.0	3.0	2.5
Ring manifold, 3-4	13.0	13.5	14.0	20.0	20.5
Ring manifold, 4-5	19.0	19.0	19.0	19.0	19.0
Ring manifold, 5-6	-	-	-	4.5	4.5
Ring manifold, 5-7	11.0	11.0	11.0	-	-
Ring manifold to cluster (3 lines), 7-8	14.0	13.0	12.0	12.5	12.5
Cluster interface to dewar A (3 lines)	3.5	3.5	4.5	4.5	3.5
Dewar A to dewar B (3 lines)	9.0	9.0	8.8	9.0	9.0
Dewar B to dewar C (3 lines)	10.0	10.0	9.8	10.0	10.0
Dewar top to beam vacuum box (9 lines)	-	-	-	4.5	7.5
Dewar bottom to vacuum box (9 lines)	0.25	0.25	-	-	-
Beam box manifold (9 lines)	16.0	16.0	-	16.0	16.0

The total line lengths are tabulated below. The placement of the refrigerator/liquefier and supply dewar has not been established for ITER; therefore, the total lineage for the distribution system is not determined. The system estimated here is for lines and use points downstream of an interface (defined as Refrigerator/supply interface) at approximately 10 m upstream from the ring manifold.

Liquid helium supply (m):	309
Cold He gas return (m):	309
Warm (>15 K) return (m):	158
Gas nitrogen return (m):	339
Liquid nitrogen supply (m):	363

The beam line dewar can be sized to either accept the regenerated helium coolant

from the cryopumps or to provide a period of uninterrupted operation in the event of refrigerator/liquefier unavailability. Cryopumps regeneration drives helium back to the dewar. The accelerator and the ion dump cryopumps contain respectively 10.55 and 11.3 liters. If the total driven back to the dewar (4 x 10.55 + 2 x 11.3) occupies 20% of the dewar capacity, the dewar volume is 325 liters. The steady state demand per beam line is 19.3 W helium (16.2 W without contingency). Assuming in a period of refrigerator unavailability that the dewar is depleted from 50% full to 10% full over a 7.5 hour period, the dewar capacity is 500 liters. A 500-liter dewar is chosen on the basis of the latter condition.
The various cryogen demands are summarized below:

Helium:

Component	Length or count		unit heat leak		Demand (w)
Liquid He supply line	309	meters	0.18	W/m	55.62
Gaseous He return line	309	meters	0.18	W/m	55.62
Valves	55		1.30	W	71.50
Bayonets	9		2.90	W	26.10
Cryopumps	9	Beam lines	16.20	W (estimated)	145.80
Dewar	9		0.15	W	1.35
			Total		355.45
			20% contingency		71.09
			Total demand (W)		427.89
			Total demand (l/hr) @ 4.2K		599.05

Nitrogen:

Component	Length or count		unit heat leak		Demand (w)
Liquid N2 supply lines	363	meters	0.29	W/m	105.27
Valves	18		4.1	W	73.80
Dewar	9		10	W	90.00
Cryopumps Accelerator	9	Beam lines	4242.72	W (estimated)	38184.48
Cryopumps Ion Dump	9	Beam lines	3340.53	W (estimated)	30064.77
			Total		68518.32
			20% contingency		13703.66
			Total demand (W)		82221.98
			Total demand (l/hr)		1891.11

The cryogen requirements for the neutral beam line system (9 beam lines excluding the demands of the liquefier/supply system and the distribution lines upstream of the interface) are 428 W liquid helium and 1891.11 l/hr (82.2 kW) liquid nitrogen.

3.5 MAINTAINABILITY

Beam line heating systems have a major impact on facilities and maintenance operations because of their large size and complexity. In order to better understand the impacts, a number of assumptions are made about the present ITER beam line concept that are discussed below. These main issues will establish maintenance requirements for beam line heating and assess their effect on the operating availability of the machine. More detailed investigations from the maintenance perspective will be needed to quantify impacts and develop design solutions.

The complexity and operating environment of each of the primary subsystems in the beam line system (ion source, accelerator, neutralizer, bending magnets, ion dumps, isolation valves, etc.) lead one to conclude that numerous unscheduled failures are likely to occur in addition to the scheduled replacements that are expected. In addition, the numerous interfaces for power, cooling, vacuum, instrumentation and controls (I&C), and structural support suggest that replacing components will be time consuming. A modular approach to the overall system design is discussed as a way to minimize downtime.

Protective structures (armor) are likely to be required on the inner surface of the plasma chamber wall to protect from inadvertent beam strikes. These can be expected to add to the remote handling activities of first wall components, and require additional maintenance and inspection equipment for in-vessel operations. In-vessel activities can be accomplished almost independently from ex-vessel maintenance operations, and will be discussed briefly.

Equipment that is located in the beam line cell(s) will become activated due to neutron streaming and require remote handling. Each beam line system will have dedicated roughing vacuum pumps, power supplies, and refrigerators. If these are located out of the beam line cell, remote handling operations are not required and maintenance for these subsystems can be done hands-on with little impact to beam line availability. If they are located in the cell, additional remote handling will be required.

3.5.1 Assumptions

The physical characteristics and maintenance requirements of the ITER beam lines are based on the configuration described by Honda (Ref. 6). Each beam line system consists of a beam line module 4 meters in diameter, 16 meters long, weighing 100 tons. The beam line subsystems are the power supplies, the ion sources, the accelerators, the neutralizers, and the ion dumps. The ion beam line module is 2.6 m in diameter and 1.6 m long; it weighs approximately 2 tons. Within these subsystems are contained the components that eventually fail by normal wear out or by unexpected breakdown. Not listed above are the vacuum vessel containment of the entire system and the support structures which complicate maintenance operations because they hinder access by the remote handling equipment. Figure 32 is a cutaway of the beam line module showing the major subsystems.

The total beam line plasma heating system consists of nine beam line modules arranged so that three modules are located at each of three adjacent plasma chamber ports. Each module contains 16 beamlets arranged in two vertical rows of eight; therefore, there are 144 beamlets. There will be some magnetic shielding around the beam line module to protect from stray fields, although reduced because the sources are approximately 46 meters from the machine centerline.

In front of each beam line module is located a vacuum isolation valve separating the vacuum confinement of the module and the vacuum of the plasma chamber. A movable neutron shield plug could be placed (although not baselined) in front of the valve. It would be closed to prevent neutron streaming when the beam line is out of service, thereby minimizing activation of the beam line components.

The beam lines are line-of-sight systems subject to neutron streaming. Neutron-induced gamma radiation will render the beam line components too activated for hands-on maintenance operations under the requirements of Federal Regulations (Ref. 7), and ALARA (Ref. 8) guidelines. Representative contact dose rate levels (Ref. 6) one day after shutdown are: 2.6-4.0 rem per hour for the neutralizer, 46.0-70.0 rem per hour for the accelerator, and 150-230 millirem per hour for the ion sources. A generally accepted criteria for radiation worker dose rate is 0.5 millirem per hour for unlimited handling, and up to 10.0 millirem per hour for limited exposure.

Most of the components that make up the beam line module are expected to have infrequent replacements occurring perhaps once in five to ten years. However, the RF-generated ion sources are expected to require replacement once per year, and the ion dumps also once per year due to high thermal/particle loads on the coolant tubes. This suggests that these subsystems should be designed for replacement as independent modules.

The machine availability requirement is 25% based on two weeks of continuous operation followed by six weeks of downtime for maintenance. Therefore, during the two weeks of uptime, the beam line systems must achieve essentially 100% availability either by having high reliability components or by having on-line spares. (This does not consider scenarios that permit degraded machine performance resulting from reduced beam heating.)

3.5.2 Configuration

The beam line heating configuration consists of three beam line modules stacked vertically at three midplane ports. Figure 33 is plan view showing the tangential arrangement around the machine, and Figure 34 is the elevation view showing the vertical arrangement at a port. The focussing of the beamlets from each beam line module is constrained by the midplane opening between outer legs of the toroidal field (TF) coils, hence the modules are limited to vertical stacking. This is an important point because from a maintenance point of view, it would be desirable to offset (stagger) the vertical arrangement for ease of vertical handling. The focussing constraint at the TF coils does not permit this.

The isolation valve (and the shield plug) is an integral part of the drift tube. The valve is located between the beam line module and the cell wall, and the plug could be installed at the cell wall to minimize neutron streaming.

There are two basic approaches to the beam line design. The first is a modular design that permits removal of individual subsystems so that failed components may be readily removed. The second is to replace the entire beam line module. Achieving the first approach appears to eliminate the second, and has the advantages of handling smaller components, potentially reducing downtime, and requiring a smaller hot cell. For both approaches, disassembly is limited to radial translation or lateral translation before lifting. Both approaches should be developed in sufficient detail to assess facility requirements, handling equipment needs, requirements for spares, and impact to machine availability.

The cells that contain the beam line modules may be arranged as separate units for each machine port, and are sized to accommodate either replacement of beam line subassemblies or complete beam line modules. If beam line modules are replaced, they may be moved radially or laterally before lifting. Radial translation will have different cell size requirements compared to lateral translation. The cell height requirements are likely to be the same for both. The wall thicknesses will be based on meeting radiation protection criteria outside the cell, as well as at the site boundary for prompt radiation and shutdown dose rates. It is likely that the wall thicknesses to meet radiation criteria will exceed the structural requirements of the facility.

A concept that could simplify access to the beam line subsystems is to design the beam line cell as a vacuum containment building, thereby eliminating the vacuum vessel surrounding the nine beam lines. Each beam line cell could be a miniature version of the NASA Space Power Facility (Ref. 9), a 100 ft. diameter, dome-shaped building capable of achieving vacuum at 10^{-6} torr. Even though this approach complicates the facility design, it could present an interesting alternative to the conventional design approaches.

The beam line facilities also include the hot cell(s) used for repairing subassemblies, replacing components, and handling solid and liquid waste that is generated as a result of operating and maintaining the beam lines. The hot cell size will depend on the design approach that is chosen for beam line maintenance.

3.5.3 Maintenance Considerations

There is considerable uncertainty in quantifying the reliability of the various beam line components that leads to uncertainty in assessing scheduled and unscheduled maintenance operations. One approach that minimizes these effects is to modularize the system based on estimating what is expected to fail. For example, the ion source should be a module that can be replaced without disturbing other "more permanent" components.

The listing in Table 1 is a subjective attempt at quantifying the subsystems and components that are likely to affect machine availability. This table can also be used to qualitatively allocate subsystem reliabilities in order to meet 25% machine availability. There are two important observations from the table. The first is that only two components are expected to have high failures due to wear out of source elements and swirl tubes. Therefore, their replacement can be planned for and should be scheduled during the six 6-week annual shutdowns that are shown in Figure 35. For the limiting cases, this may be accomplished by replacing the sources in one and a half beam lines during each of the six scheduled shutdowns to achieve total replacement during the year; or replacement of three beam lines during the last three annual shutdowns. (Obviously, other combinations are possible between these two boundaries but are not discussed.)

The first scenario is not credible because once a beam line module is disturbed, all the components that are expected to fail should be replaced. Therefore in the second scenario, after the first six months of machine operation, a regular annual replacement schedule for source grids and ion dumps may be established. This means that these scheduled maintenance operations cannot exceed two weeks for each beam line module replacement. It is also likely that at perhaps half of the scheduled downtime (6 weeks per shutdown) will be allocated to unscheduled events; therefore, one week per scheduled beam line activity is a likely design requirement for beam line modules and ion dumps.

The second observation is that the impact to machine downtime can be minimized if many of the subsystems are located outside of the beam line cell where they can be maintained hands-on, possibly without machine shutdown. Vacuum pumping equipment for cryopanel regeneration, coolant pumps and filters, main power supplies, and I&C are examples.

Maintenance operations can only occur in the beam line cell when the machine is not operating to ensure that the maintenance equipment does not become activated. In situ repairs are those accomplished remotely in the beam line cell in lieu of operations in a hot cell. For example, repairing an ion beam line module in situ may reduce the requirements for hot cell equipment and space, but the serial nature of the operations are likely to impact machine availability. In situ operations appear valid only if spare modular components are not available.

Hot cell repairs are by nature operations that occur parallel to operating the machine if spare components are available. Clearly, this approach has the least impact on machine downtime.

The design of the beam line will greatly affect the maintenance requirements of the beam line cell and the hot cell. If a modular approach is chosen whereby each subsystem is removed independently from adjacent subsystems, it is clear that the beam line cells and hot cells can be smaller than if the entire beam line module must be handled.

Determining which subsystems and components require spare modules and the number of spares needed depends on understanding the mean time to repair (or replace) (MTTR) and the mean time between failures (MTBF). In Table 1, ion sources and swirl tubes were identified to require frequent, scheduled replacements. If it can be shown that the time to repair these modules is less than the six weeks of machine downtime, spares may not be required provided that facilities and maintenance equipment can be dedicated to achieving these repairs. However, if module replacement can only be accomplished during the shutdown periods, then spares are needed and repairs on the failed modules are accomplished in the hot cell before the next scheduled shutdown.

The need for spare modules should be evaluated on the basis of impact to cost and machine downtime. In some instances it will be cost effective to impose requirements on the design of a module design to make it repairable quickly, thereby avoiding the need for spares.

Service connections are required for power supplies, cryogenics, vacuum, instrumentation and controls, and water cooling. For remote handling, these must be reliable, accessible, and simple to use. Where connections are not expected to be disassembled, permanent installations such as brazed or welded joints usually provide the degree of reliability needed. However, because of the modular disassembly required to replace or repair the subsystems and components of the beam lines, interfaces that can be readily decoupled are needed.

Power supply connections can be made up using spring-mounted, male-female connectors (Ref. 10) of the type being considered by the Compact Ignition Tokamak (CIT) for TF coil connectors. Use of cryogenic connectors must consider the reentrant space required for the bayonet-type interfaces, as well as handling double-walled pipes and insulation at joints. Mechanical vacuum joints using Cefilac/Helicoflex couplings have been successfully used at the Joint European Torus (JET), and will developed further for CIT. Electrical connectors for instrumentation lines and data links are available with remote handling features from several sources (Ref. 11), and are in use at JET and Oak Ridge National Laboratory, and planned for use in CIT. Quick-disconnect fluid couplings are also available from a number of sources, but are likely to require some development to enhance sealing capability; they have a tendency to leak. A more reliable solution is to use the Cefilac coupling if coolant lines are not larger than 5 to 8 centimeters in diameter.

The beam line module vacuum vessel will have many circumferential joints if it is modularized by subsystems. These joints may have a large diameter mechanical seal with many bolts, or few bolts with a welded lip seal. The former approach is time consuming, the latter requires developing a tool to remotely cut and weld lip seals. A design study is needed to determine the cost-effective approach.

Support structure for the vertical arrangement of beam line modules will limit access to the interface connections and hinder removal of beam line modules or modular subsystems. Figure 36 is an elevation view of a support structure concept. In this approach, the structure for each beam line is an integral part of the beam line module, and either the beam line cell must have enough lay down space for two beam lines, or that space must be provided in a hot cell. The support structure must be designed to meet seismic criteria.

The beam line system requires vacuum isolation so that beam line modules may be maintained or removed without disturbing the vacuum integrity of the plasma chamber. One valve installed in the drift duct is required. A second may be needed to seal the beam line module, although that appears to be a questionable requirement. The valve interface to the drift duct must be accessible by remote handling equipment, and the valve assembly must be modularized to permit easy replacement of components that are expected to fail, such as actuators and seals. The valve body may be joined to the duct by welding, bolting with mechanical seals, or lip seal welded. The choice depends on the permanency of the assembly based on reliability analysis. The valve and its components should include features that allow access to electrical/pneumatic connections.

Similar requirements apply to the neutron shield shutter if needed. The shutter installation is perhaps more difficult because it is installed in or very near to the cell wall, and will also have active cooling connections for water.

Over the life of machine operations a considerable amount of solid waste will be generated resulting from worn out source grids, swirl tubes, and other component failures. Liquid waste will also be generated from activated and contaminated cooling water.

Provisions for solid waste compaction should be included in the hot cell design, along with space for shielded storage or disposal of solids in shielded casks. Storage tanks for liquid waste, and the means for storing or disposing of a stabilized form of liquid waste must also be included.

3.5.4 Maintenance Operations

In situ replacement of the entire beam line module with a spare, and its removal to the hot cell for repairs is one approach for achieving the required availability of the beam line system. Another approach is to modularize the beam line system so that sub-modules may be disassembled in situ and replaced with smaller spares. Both approaches must be developed in sufficient detail so that trade studies can be used to assess which is the cost-effective approach. The differences between the approaches that are likely to emerge from studies are beam line cell size, hot cell size, crane requirements, contamination containment, maintenance equipment, and downtime (MTTR).

Regardless of which approach is chosen, there are certain operations that are common to each. In general, these include the preparations to the maintenance equipment, breaking the vacuum integrity of the beam line vessel and possibly baking to minimize tritium outgassing, and purging and storing dielectric gas (SF_6), coolant (water), and cryogens (LN and LHe).

All of the issues discussed in the preceding sections deal with remote maintenance beam line considerations that are accomplished external to the machine, in the beam line cell or in the hot cell. In addition to these, there are a limited number of activities that occur in the plasma chamber which require support from the maintenance equipment in the experimental hall. These deal with repair or replacement of the beam dumps (armor) that are mounted to the first wall at the beam lines-of-sight.

Presumably, beam dumps will not be items for scheduled maintenance. However, since their replacement is not a trivial operation an assessment is required to determine the impact to machine availability, the need for special end-effector tools to accomplish in-vessel manipulator operations, the interaction with the ex-vessel manipulator system, and space requirements in the test cell. The primary finding is likely to be identification of special tools needed for disassembling and handling armor in the plasma chamber, and other equipment such as a lifting fixture and a contamination container for subsequent handling in the test cell.

3.5.5 Maintenance Equipment

Maintenance considerations for beam lines include identifying the equipment and tools needed to accomplish repair and replacement of components, the commercial availability of equipment and tools, and the R&D programs necessary to develop equipment and tools that do not exist. The items needed in the beam line cell include, but are not limited to:

* overhead crane system
* floor-mounted jib cranes
* overhead boom/manipulator(s)
* viewing systems
* cutting/welding tools
* lifting fixtures
* end-effector tools
* various contamination containers

Furthermore, if parallel operations are required in adjacent beam line cells to meet machine availability, multiple sets of dedicated maintenance equipment and tools may be needed. Time and motion studies based on achieving 25% operating availability are required to quantify the equipment needs.

The equipment needed in the hot cell includes, but is not limited to:

* overhead crane system
* rail-mounted transporter
* overhead manipulator
* turntable work stations
* work station manipulator
* cutting/welding tools
* end-effector tools
* compacter
* shielded windows
* shielded casks
* viewing systems
* source conditioner

The test cell equipment needed to support beam line maintenance (armor replacement) is limited to end-effector tools used by an articulated boom manipulator for in-vessel operations, fixtures to handle armor modules, and contamination containers.

3.5.6 Facilities

Lay down space is required in the beam line cells, the hot cell, and the test cell, to temporarily store components and equipment during maintenance operations. The space requirements are determined by developing detailed scenarios that account for every procedure necessary to repair or replace the various beam line subsystems and components.

For example, considering the approaches for lateral beam line removal, the additional floor space required to store the middle and top beam line modules in order to remove the bottom module is great, and will add to the facility size. Facility cost will be greatly affected in this case because cost is a function of enclosed building volume.

Lay down space in the hot cell is based on whether beam line modules or sub-modules are to be handled.

Lay down space is likely to be required in the test cell if beam dumps are removed while maintenance operations are underway for other systems.

Storage space is required for the maintenance equipment that is dedicated to beam line systems, for new (unactivated) spare components, and for refurbished (activated) spare components. The amount of required space is based on whether entire beam line modules or sub-modules are handled, and on the quantity of spares. The storage of maintenance equipment must be outside the beam line cell(s) and the hot cell to preclude neutron-induced activation and to permit hands-on maintenance of the maintenance equipment, respectively.

3.6 POWER DISTRIBUTION

The power distribution in the beam line module is estimated from the neutralizer efficiency (LBL data) and from beam losses derived earlier.

Neutralizer efficiency:	61%
Transmission efficiency:	97%
Reionization loss:	5%
Delivered current per beam line (Amps):	7.92
Accelerator current required (Amps):	14.09
Per Beamlet:	0.88

Power distribution per beam line (MW)

Delivered:	10.29
Drift duct and ion dump compartment:	0.92
Transmission:	0.55
Un-neutralized:	7.14
Total:	18.90 MW

3.7 SYSTEM COST

In 1987 Grumman costed a neutral beam line system for the US version of the device that has now evolved as ITER. The level of definition of the beam line now offered for ITER is comparable to that of the system for TIBER which was the earlier US concept. The TIBER cost estimating was reviewed as an indication of the expected cost of the ITER system, which is the subject of this report.

The TIBER beam line system comprised two beam lines, each capable of injecting into the plasma, 25 MW D^o at an energy level of 500 keV. Each beam line comprised two arrays of 10 sources each with each source having 240 beamlets (channels). Neutralization was by gas cell, and the machine's vertical magnetic field deflected the un-neutralized ions to the dumps. Commissioning of the beam line was not a specified requirement, and thus maximum fluxes on the dump were considerably lower than projected for the ITER dumps. However because the machine's field varied widely as the plasma current was varied, the dump length was equal to the length of the drift duct. The beam lines were not modular, although remote handling capabilities were provided for servicing of the ion sources.

A WBS was devised for the TIBER system for the purpose of estimating cost, which was derived from Grumman cost estimating methodology for estimating high technology systems to be engineered and manufactured at the company's facilities.
Relationships in terms of dollars per unit of weight or volume were developed from historical data, including data from prior fusion devices. The cost estimate of individual items (there were 51 identified items in the TIBER study) was projected to deviate up to 20%, although the overall cost variation was expected to be less of a variation.

Although the ITER and TIBER beam line systems are different in configuration, their levels of complexity (simplicity) are comparable: Source: Fewer beamlets but at higher energy level; Neutralizer: Comparable; Ion dump: Smaller but with magnet deflector and at higher energy; Vacuum and cryogenic systems: Comparable; Subsystems: More units per beam line system but fewer per (modular) beam line; Beam lines: More beam lines but more compact arrangement per line.

On the basis of this qualitative assessment, the unit cost on the ITER beam line is not expected to exceed that of projected for the TIBER system (excepting inflation) which was $3.60 (1987 constant year dollars) per watt of injected power.

4 - CONCLUSIONS

The highlights of the program are summarized below:

The performance of the gas cell neutralizer is improved by satisfying these conditions:

* Injection of the neutral gas at 25% of the distance from the neutralizer box inlet to the exit.
* Addition of baffles at the edge of the beam in the neutralizer to retard passage of the gas particles out of the neutralizer.
* Widening the neutralizer to increase the residence time of the gas.
* Tapering of the top and bottom surfaces of the neutralizer.

An ion dump has been described that will withstand the commissioning and operational power deposited projected for the ITER beams. Development is required to validate the swirl tube heat exchanger for the high commissioning heat loads.

A regenerable cryopump system for continuous system beam line operation has been described. The distribution system on the beam line is more complex than that which would be required for a beam line designed for off line regeneration. This complexity is not expected to affect the removal of a beam line for maintenance.

The cryogen requirements for the beam line cryopumps are well within the amount allocated by the ITER team.

The beam line (module) accelerated power, excluding the power supply losses required to deliver 10.29 MW, is 18.90 MW.

Beam line maintenance is formidable not only because the modules are large and complex, but also because there are nine systems with an inordinate number of subsystems and components. The maintenance equipment that will be used is likely to be dedicated to those systems, and the maintenance related facilities will significantly add to the facility cost.

Several considerations were identified that should be factored into the design trade studies for completeness. They include identifying the maintenance equipment needed not only in the beam line cell(s) but also the equipment needed in the hot cell and test cell; facility requirements for lay down and storage space; activities that interface with in-vessel and ex-vessel test cell manipulators; and waste handling equipment and facilities.

It is clear from the discussions that detailed design studies are needed to evaluate the options that exist regarding beam line modularization, disassembly approaches, impact to machine availability, maintenance equipment needs, facility requirements, and total cost. These should be carried out in sufficient detail in collaboration with the beam line system designers so that reasonable requirements will be established for the beam line system and the maintenance system. The figures of merit for assessing each approach should be the cost of equipment, spares, and facilities, and the impact to machine availability.

5 - REFERENCES

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Subsystem	Probability of Failure	Handling
A) Located in the Beam Line Cell		
Accelerator		
Ion Source	High (1)	Remote
Power Supplies	Low	Remote
Cryopumps	Low	Remote
Neutralizer	Low	Remote
Ion Dump		
Dumps	High (1)	Remote
Cryopumps	Low	Remote
B) Located out of the Beam Line Cell		
Power Supply	Low	Hands-on
Vacuum Pumping	Low	Hands-on
Cooling	Low	Hands-on

(1) Scheduled repair

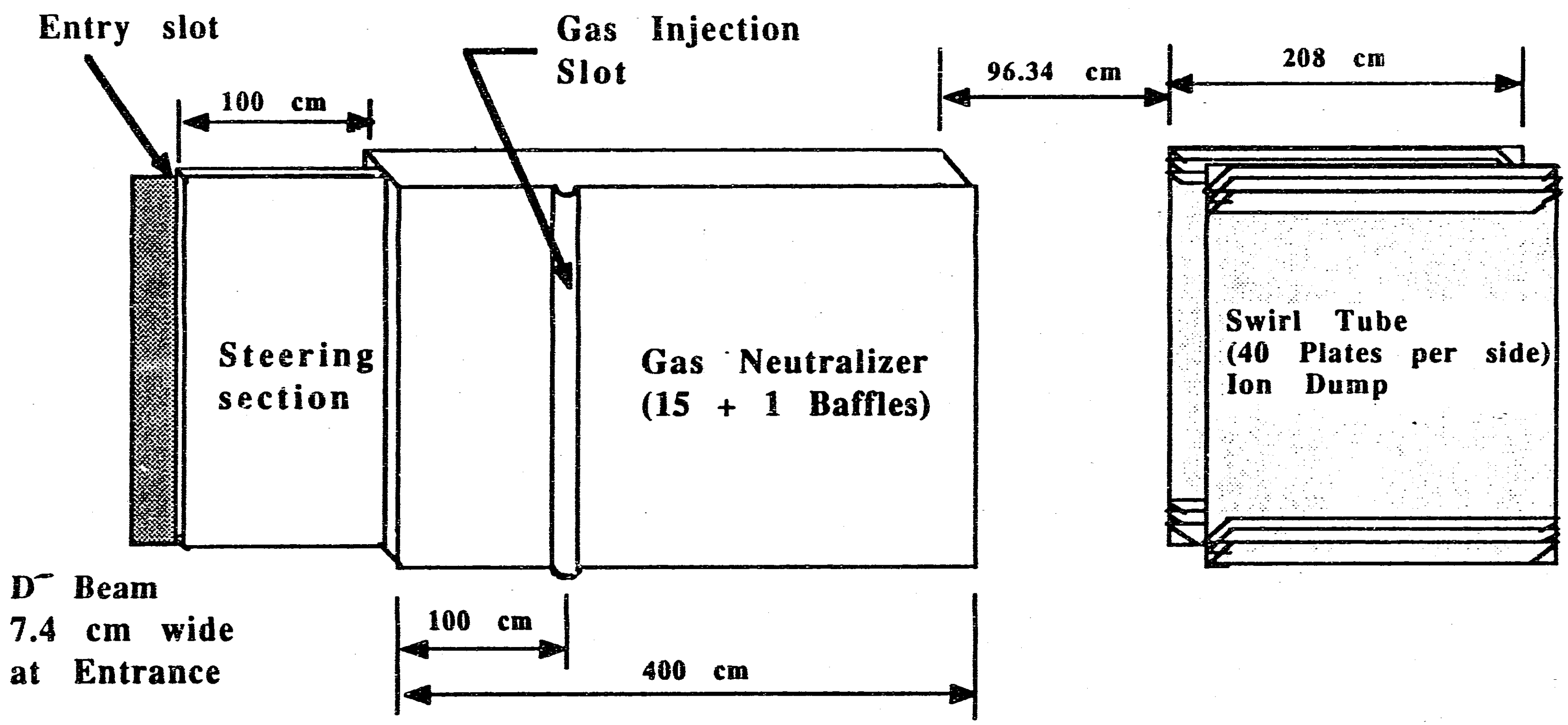
Table 1 - Beamline Subsystems Expected to Fail, and Maintenance Handling

Nomenclature	Definition
Accelerated D^- current	Total current per module measured at the accelerator exit
Accelerator	Subsystem for acceleration of directed ions
Array segment	Vertical group of channels in an assembly in which the channels' aiming is parallel
Average source current density	Current density at source exit measured with respect to the source area
Beam divergence	Half angle of channel at the e-fold
Beam energy	Final energy of beam delivered to the torus
Beam line	Complete assembly comprising source to neutralizer with all ancillary subsystems (power supply, vacuum container, pumps, etc.)
Beam line aiming distance	Distance along beam from accelerator exit to TF coil aperture (Za in LBL nomenclature)
Channel	Individual beam from source
Channel area	Cross-sectional area of channel at a given station
Cluster	Group of beam lines aimed through a common aperture
Current per channel	Current of each channel measured at the accelerator exit
D^- curr density at source	Current density with respect to source channel area measured at the extraction aperture
Extraction aperture area	Channel area at plasma generator/accel entrance
Source	Plasma generator and extractor for production of directed negative ions
Source area	Frontal area of source per channel
Source array	Group of array sources in a vertical arrangement, where each array may be focused separately
TF coil aperture	Location between TF coils where the coil aperture width and height are given

Figure 1 - ITER Beam Line Definitions

Parameter	FY 1989	FY 1990
Accelerator output per beamlet (Amps)	0.14	0.88
Neutralizer efficiency	0.58	0.61
Transmission efficiency	0.99	0.97
Beamlet (beam) dia. at accel. exit. (cm)	1.6	6.0
Channel spacing (cm)	4.42	22.0
No. of sources (segments) per array	3	2
Spacing between segments, hole to hole	12	58
Delivered current per module (Amps)	6.87	7.92

Figure 2 - ITER Beam Line Changes



Note:
* Dimensions are not to scale.
* Effect of radiation shield geometry on neutralizer shape not accounted for.

Figure 3 - Arrangement of Neutralizer & Ion Dump (2 per Beam Line)

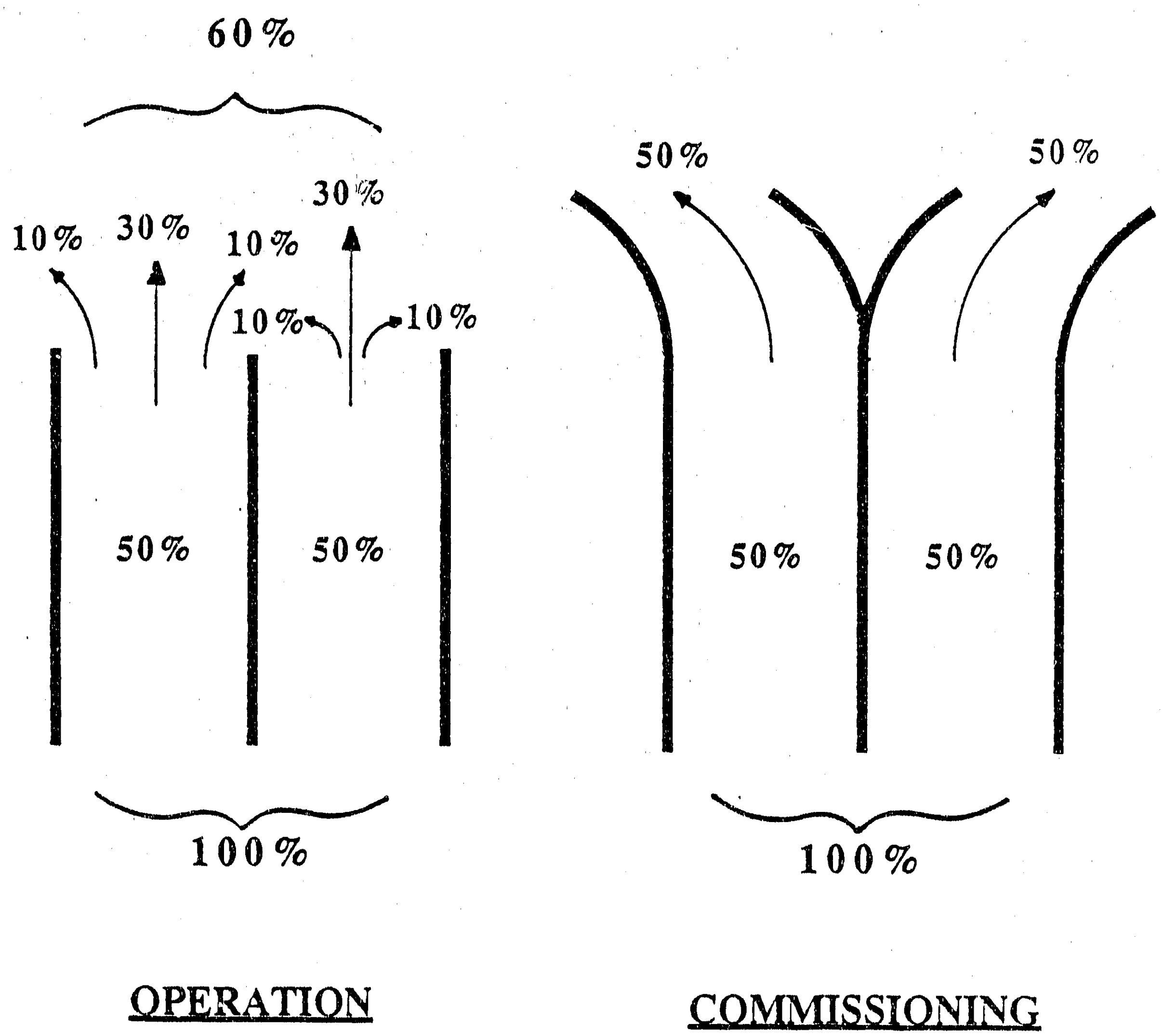


Figure 4 - Distribution of Beam Power from the Two Source Arrays

Figure 5 - Distribution of Heat Flux Crossing Ion Dump Plane Along a Vertical Line at Locations of Maximums Along Beam Line

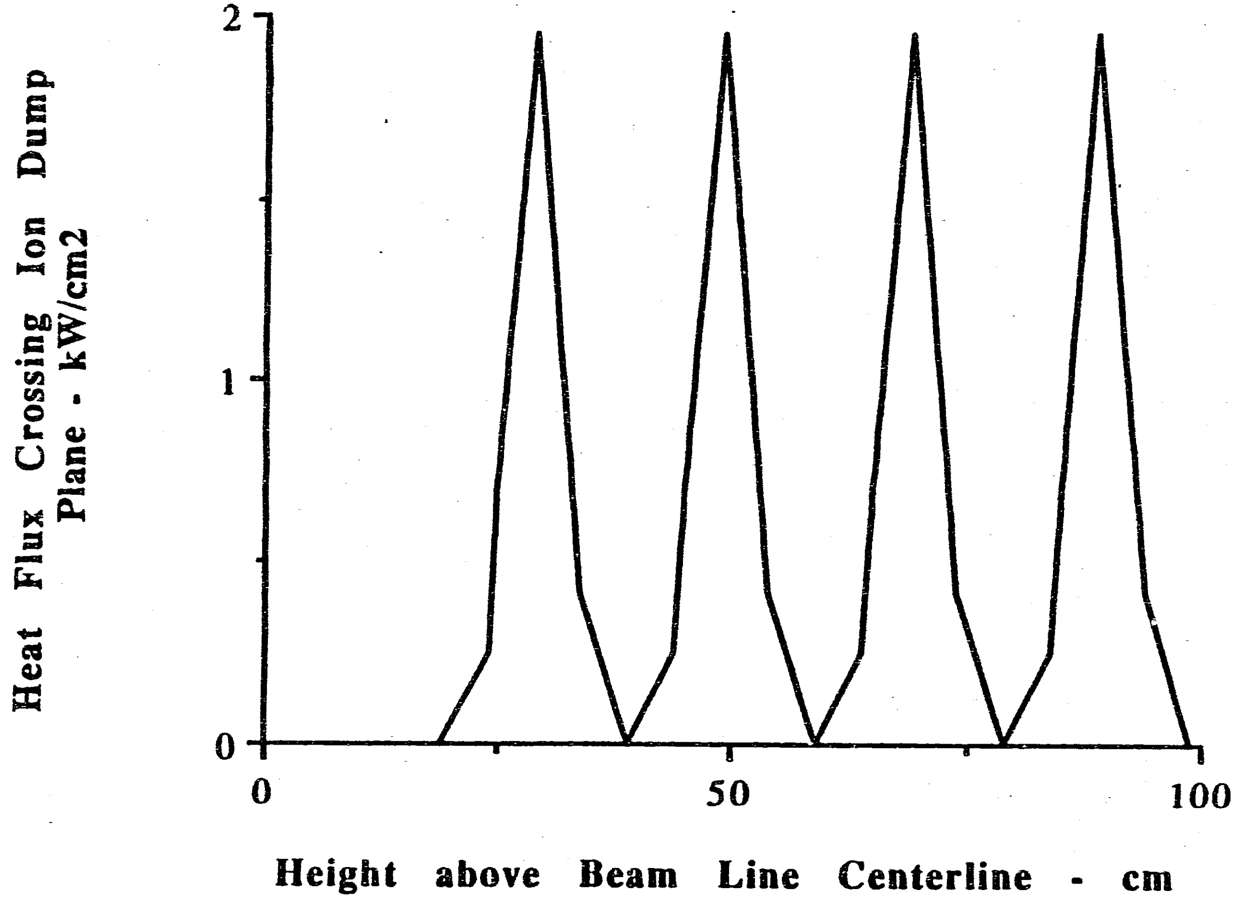
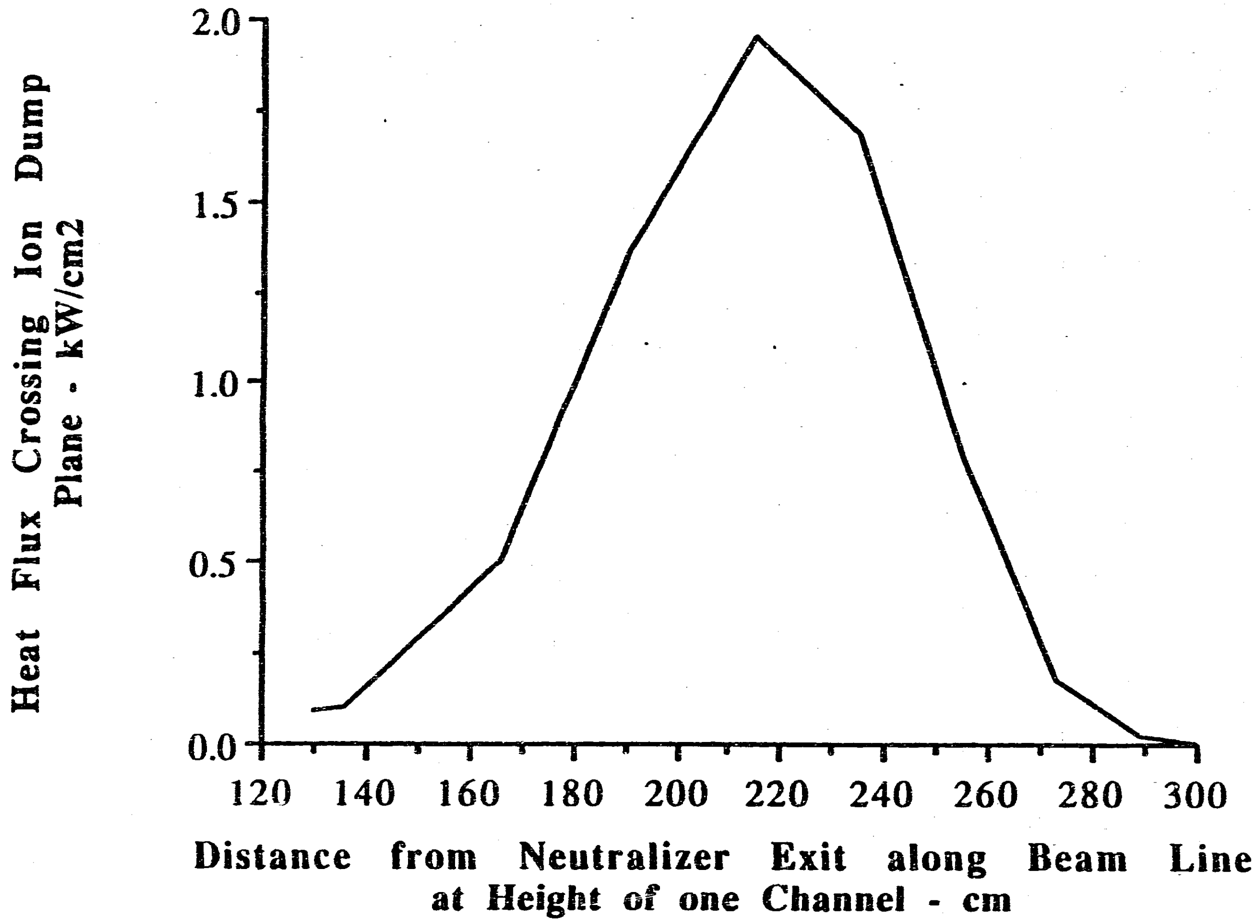


Figure 6 - Distribution of Heat Flux Crossing Ion Dump Plane Along a Line in the Beam Direction at Location of a Channel Centerline



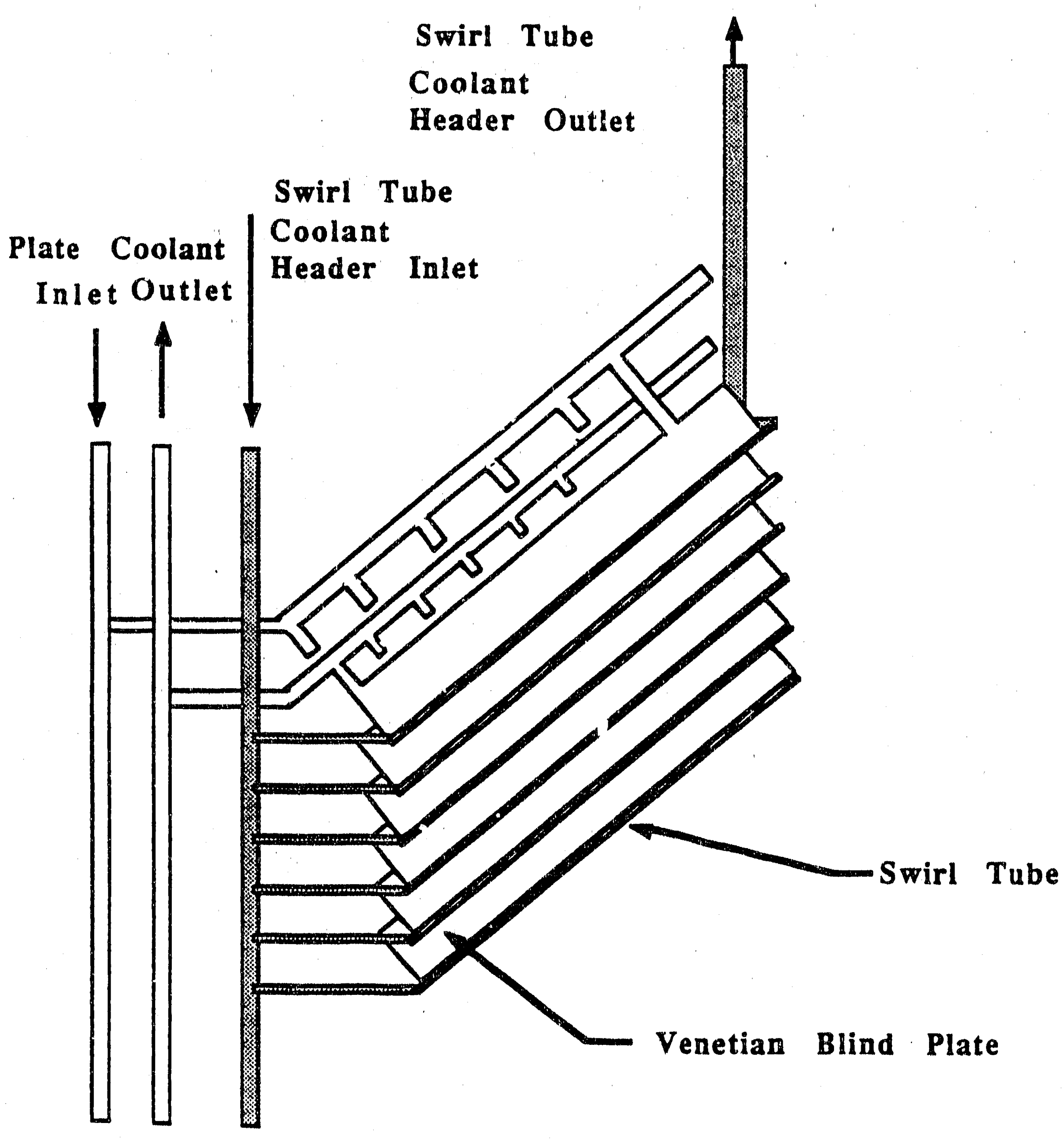


Figure 7 - Trimetric View of Horizontal Venetian Blind Ion Dump with Coolant Header Configuration

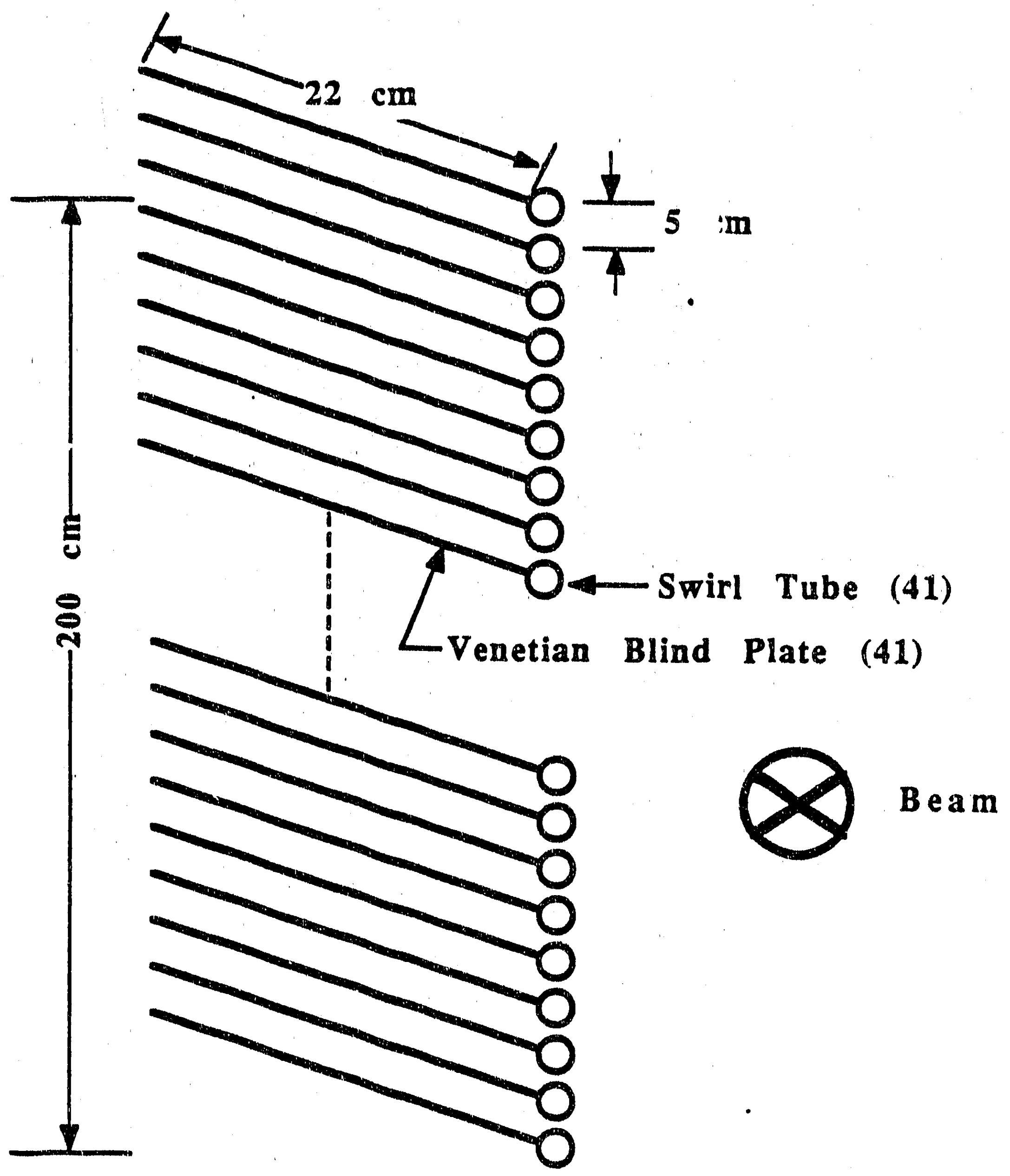
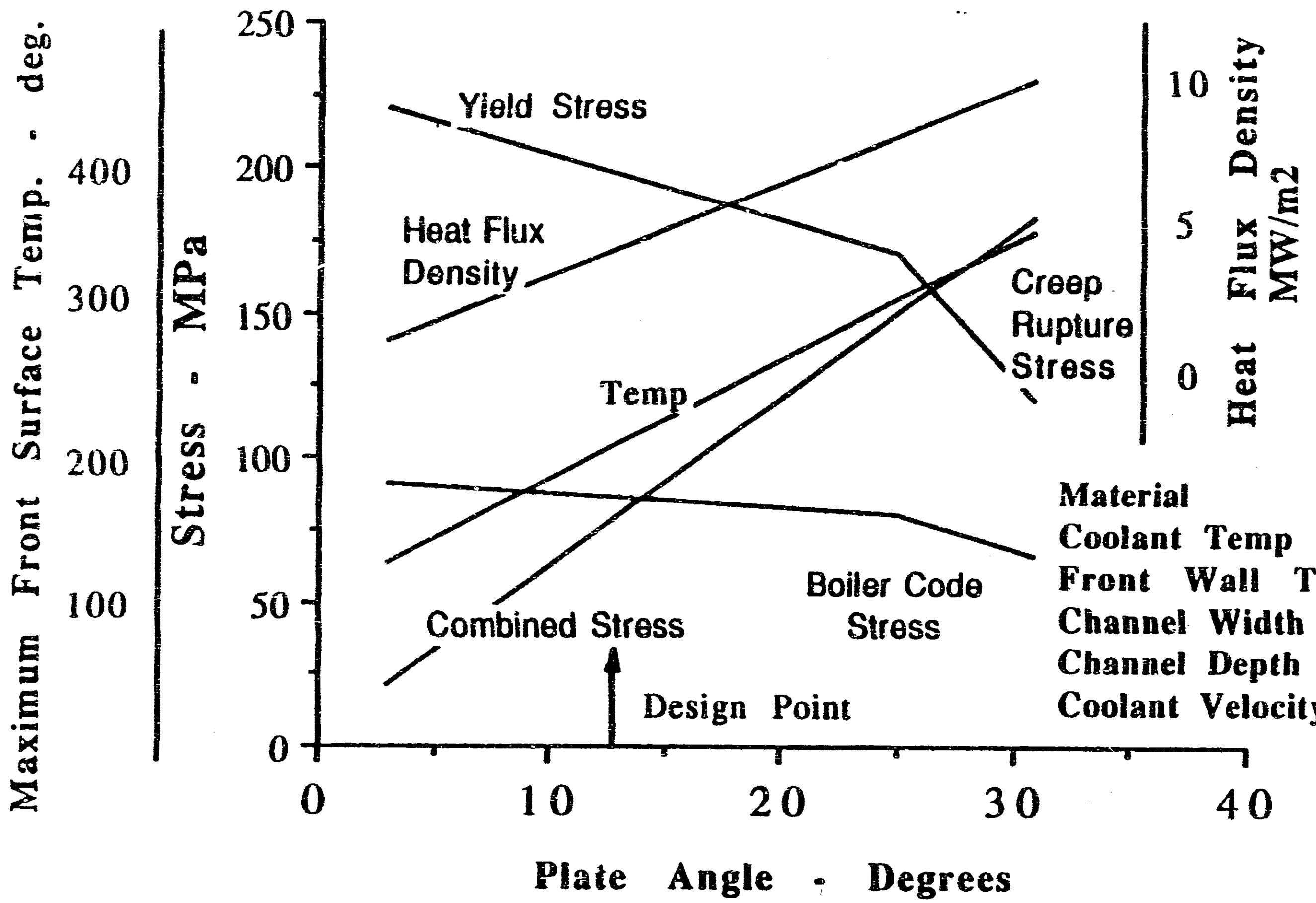


Figure 8 - Commissioning Horizontal Venetian Blind Ion Dump Transverse View

Figure 9 - Beam Line Ion Dump Venetian Blind Plate - Stresses, Temperature, Heating vs Plate Angle



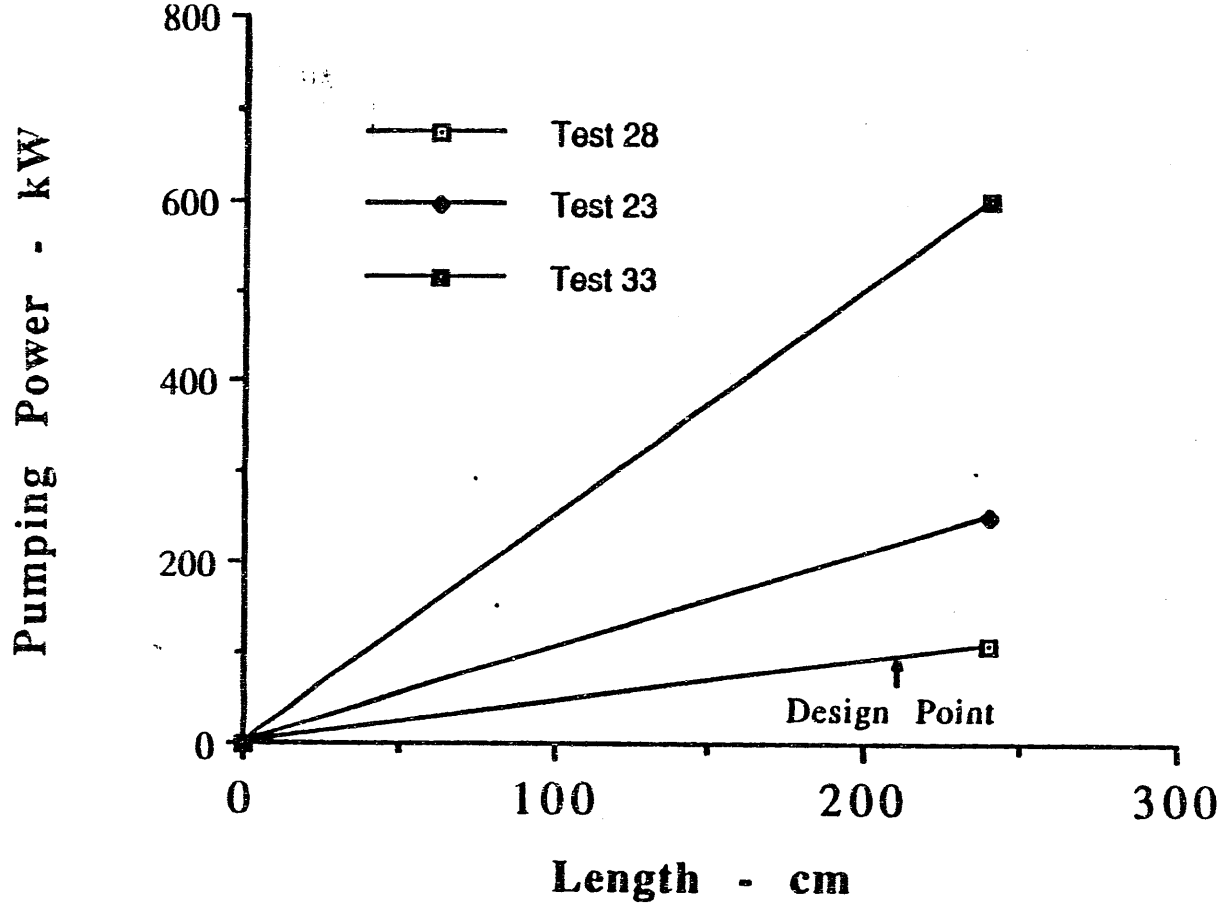
Material	ZrCu
Coolant Temp I/O (C)	30/98
Front Wall Thickness (cm)	0.3
Channel Width (cm)	0.6
Channel Depth (cm)	0.2
Coolant Velocity (m/s)	9

Test Case	OD (cm)	ID (cm)	Max Heat Flux (MW/sq m)
23	0.52	0.35	29.6
28	0.68	0.48	43.5
33	0.35	0.35	41.3

Note: Data From Ref. 2

Figure 10 - Swirl Tube Specifications

Figure 11 - Leading Edge Swirl Tubes for the Venetian Blind Plates - Total Pumping Power vs Length of Plates

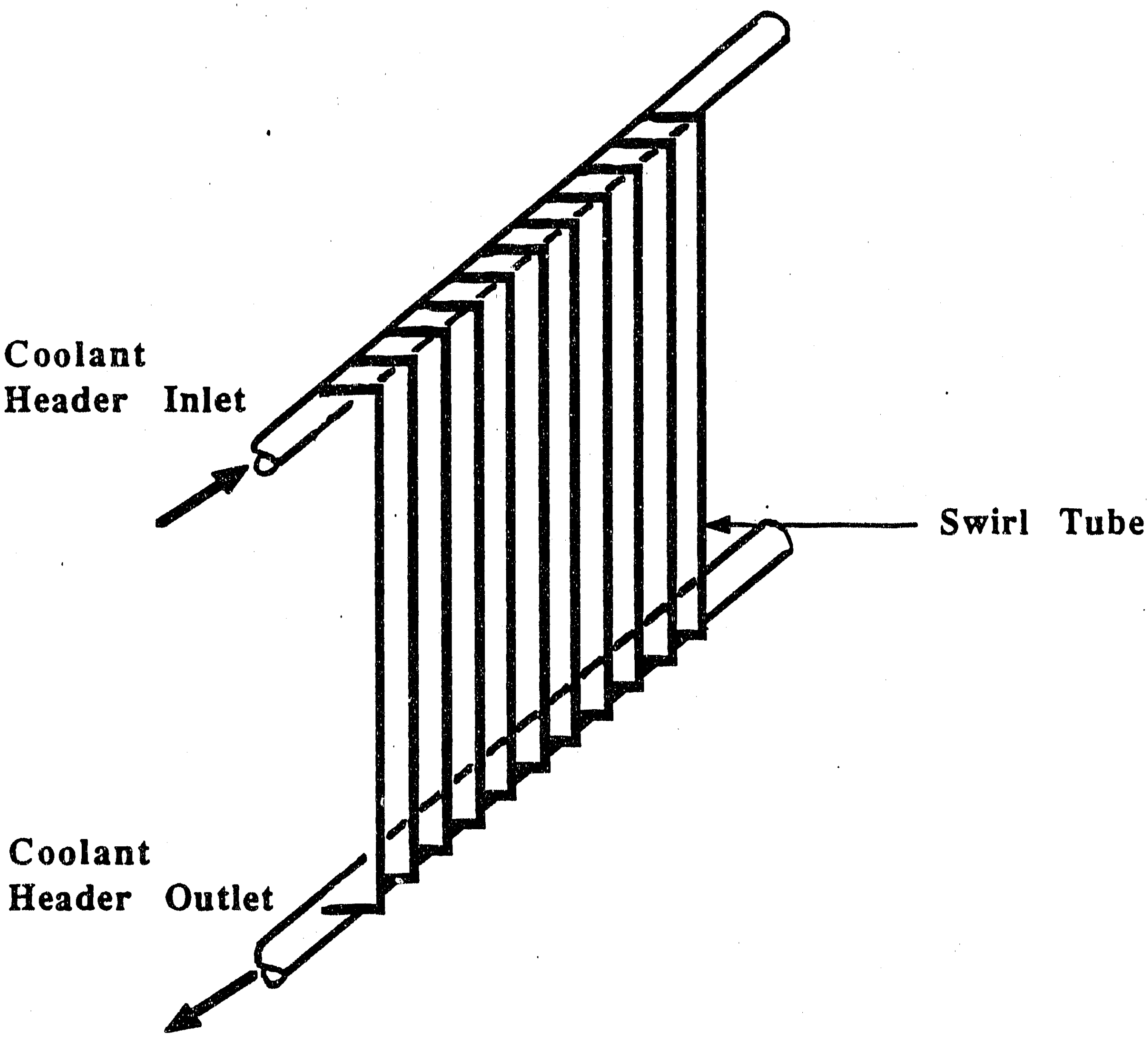


Material	ZrCu
Number of Plates	41
Plate Length (cm)	208
No. of Coolant Channels / Plate	260
Plate Width (cm)	22
Vertical Distance between Plates (cm)	5
Plate Sweep Angle (deg)	13
No. of Coolant Channels in series	4
Front Wall Thickness (mm)	3
Rear Wall Thickness (mm)	1.8
Coolant Channel Size (mm X mm)	6 X 2
Plate Thickness (mm)	6.8
Weight: 40 Plates (kg)	1108
Max Heat Flux (MW/sq m)	4.34
Max Coolant delta T (C)	68
Avg Coolant delta T (C)	14.4
Max Plate Surface temperature (C)	210
Coolant System Static pressure (Pa)	9.7e4
Coolant System delta pressure (Pa)	1.9e5
Max System pressure (Pa)	2.87e5
Max Pressure Stress (MPa)	0.57
Max Thermal Stress (MPa)	78.9
Max Combined Stress (MPa)	79.6
Boiler Code Stress (MPa)	79
Coolant Velocity (m/s)	9
Coolant flow rate (m^3/s)	0.28
Coolant Pumping Power (kW)	54

Figure 12 - Specifications and Performance of Venetian Blind Plates (per side)

Material	Cu
Number of Tubes	41
Tube Length (cm)	208
Inner Diameter (cm)	0.48
Outer Diameter (cm)	0.683
Weight: 40 Tubes (kg)	14
Coolant System delta pressure (Pa)	3.98e6
Max Power on Tube (kW)	112
Tube Heating Power Capacity (kW)	190
Max Heat Flux (MW/sq m)	19.3
Heating Flux Capacity (MW/sq m)	43.5
Coolant Velocity (m/s)	26.8
Coolant flow rate (m^3/s)	0.02
Coolant Pumping Power (kW)	80

Figure 13 - Specifications and Performance of Leading Edge Swirl Tubes for the Venetian Blind Plate (per side)



Additional Swirl Tube Specifications for the Vertical Tube Design

No. of Swirl Tube	203
Length (cm)	200
Spacing (cm)	1.03
Pumping Power (kW)	397
Weight: 203 Tubes (kg)	466

Figure 14 - Trimetric View of Full Surface Ladder Ion Dump with Coolant Header Configuration

Figure 15 - Effect of Inlet Section Barriers

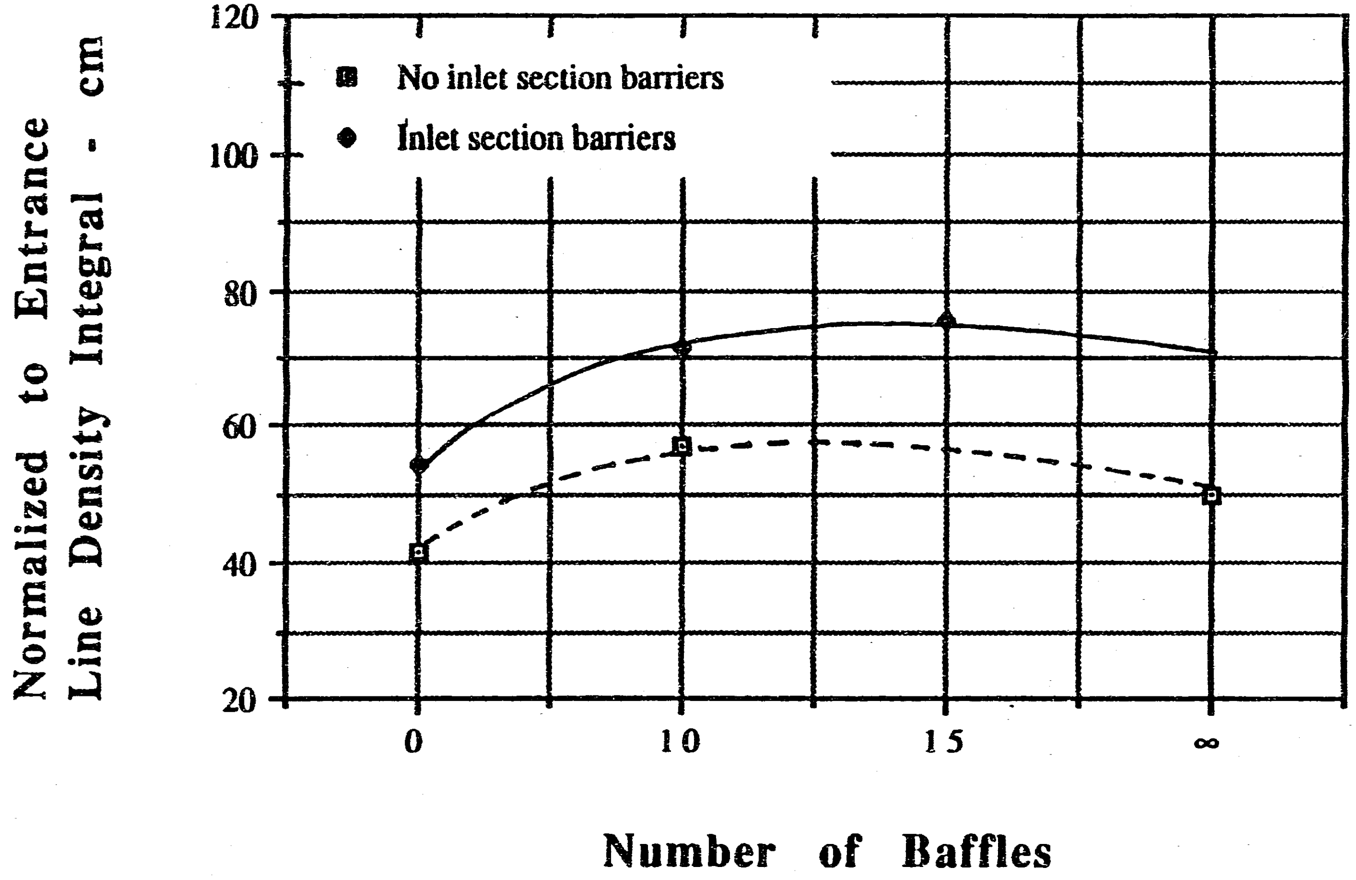


Figure 16 - Effect of Injection Location on Line Density Integral

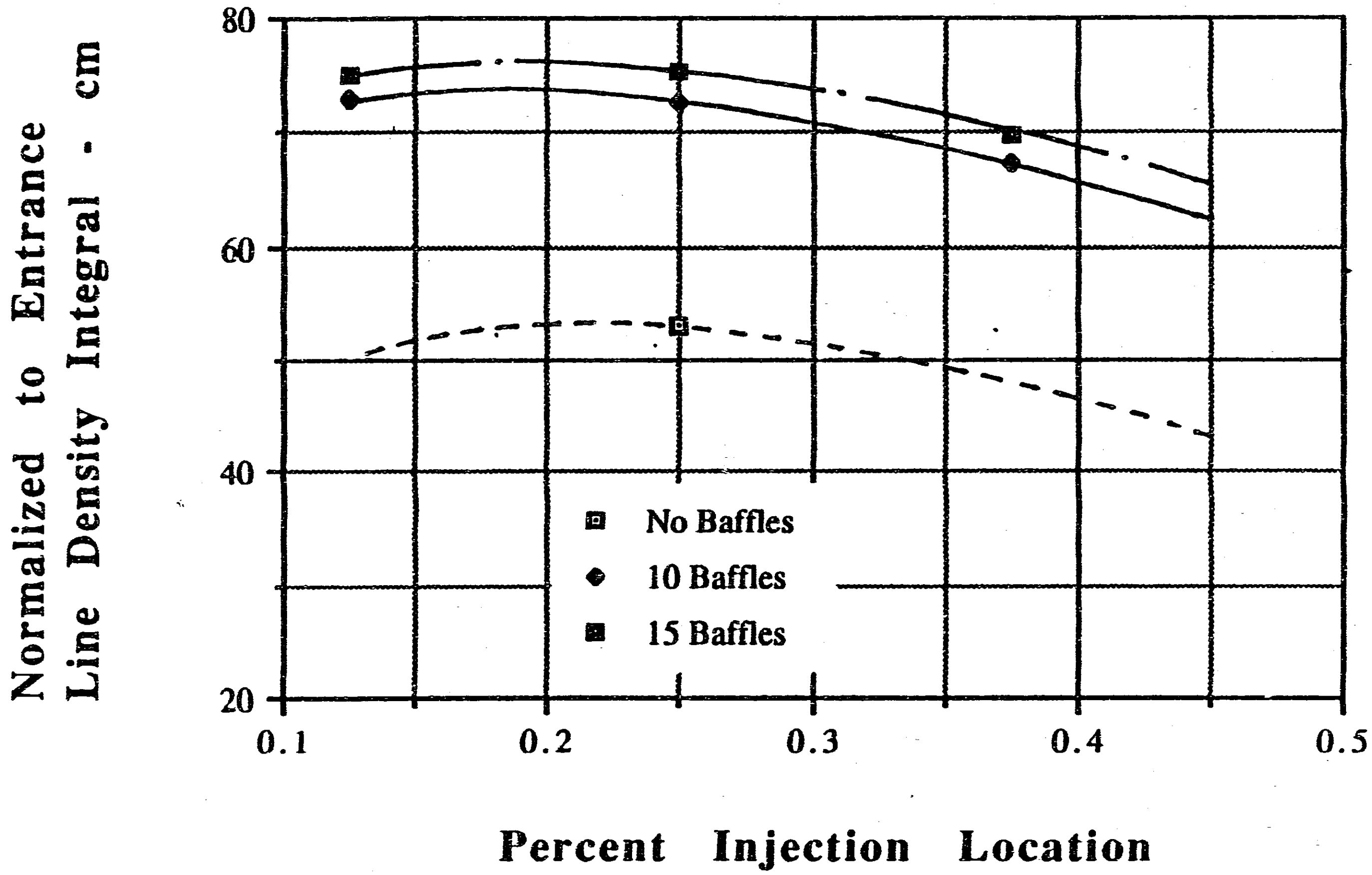


Figure 17 - Comparison of Width Effect on Line Density Integral

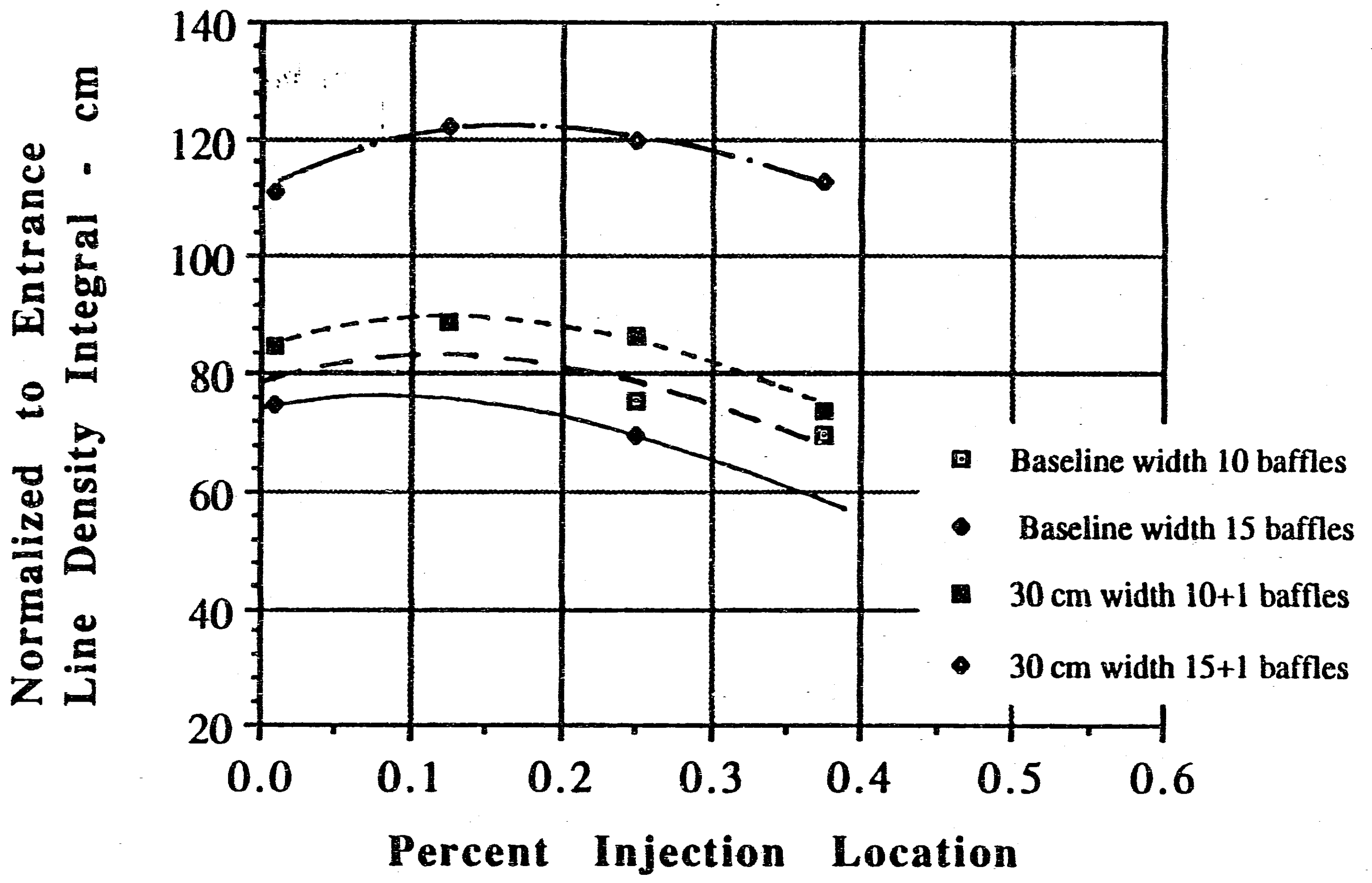


Figure 18 - Baffling and Width Effect on Ion Dump Gas Load

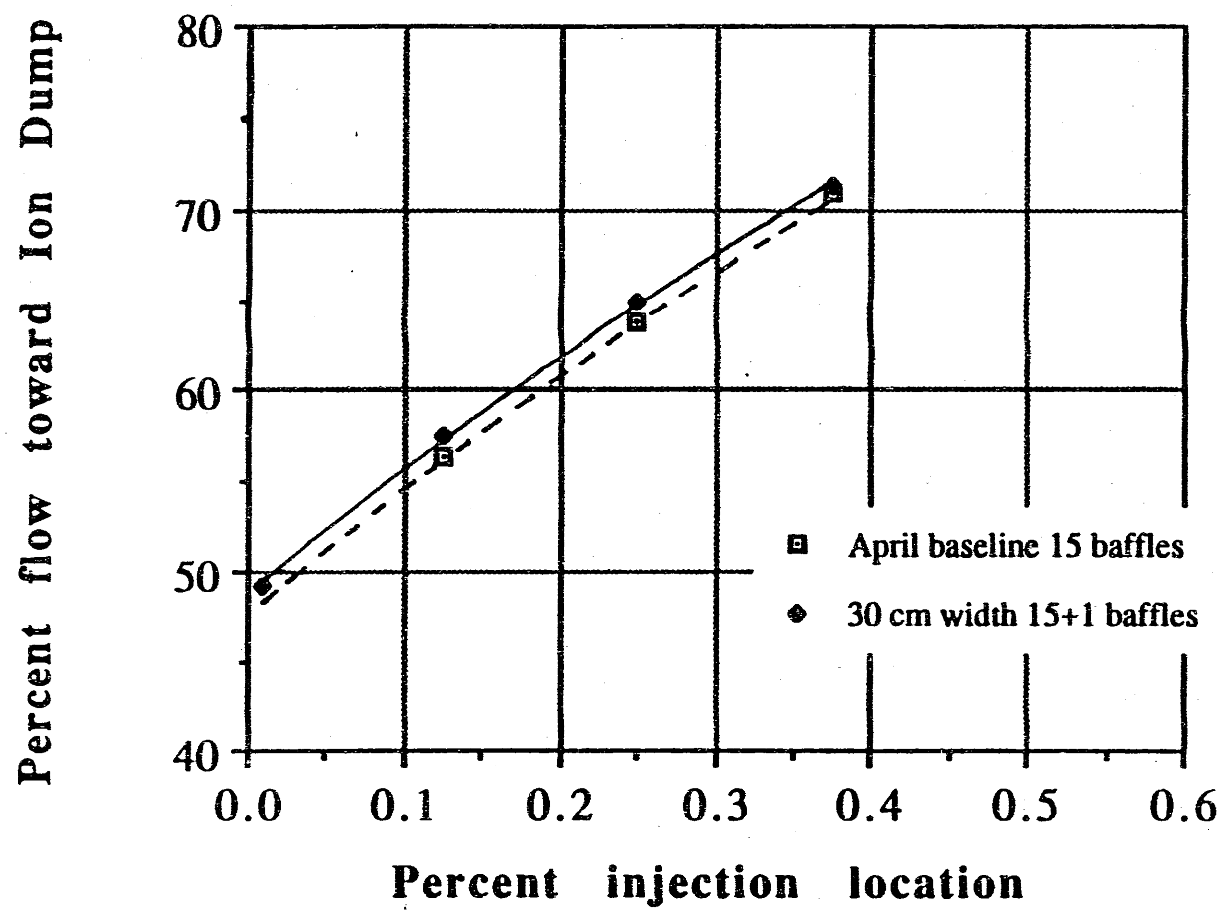


Figure 19 - Maximization of Neutralizer Width

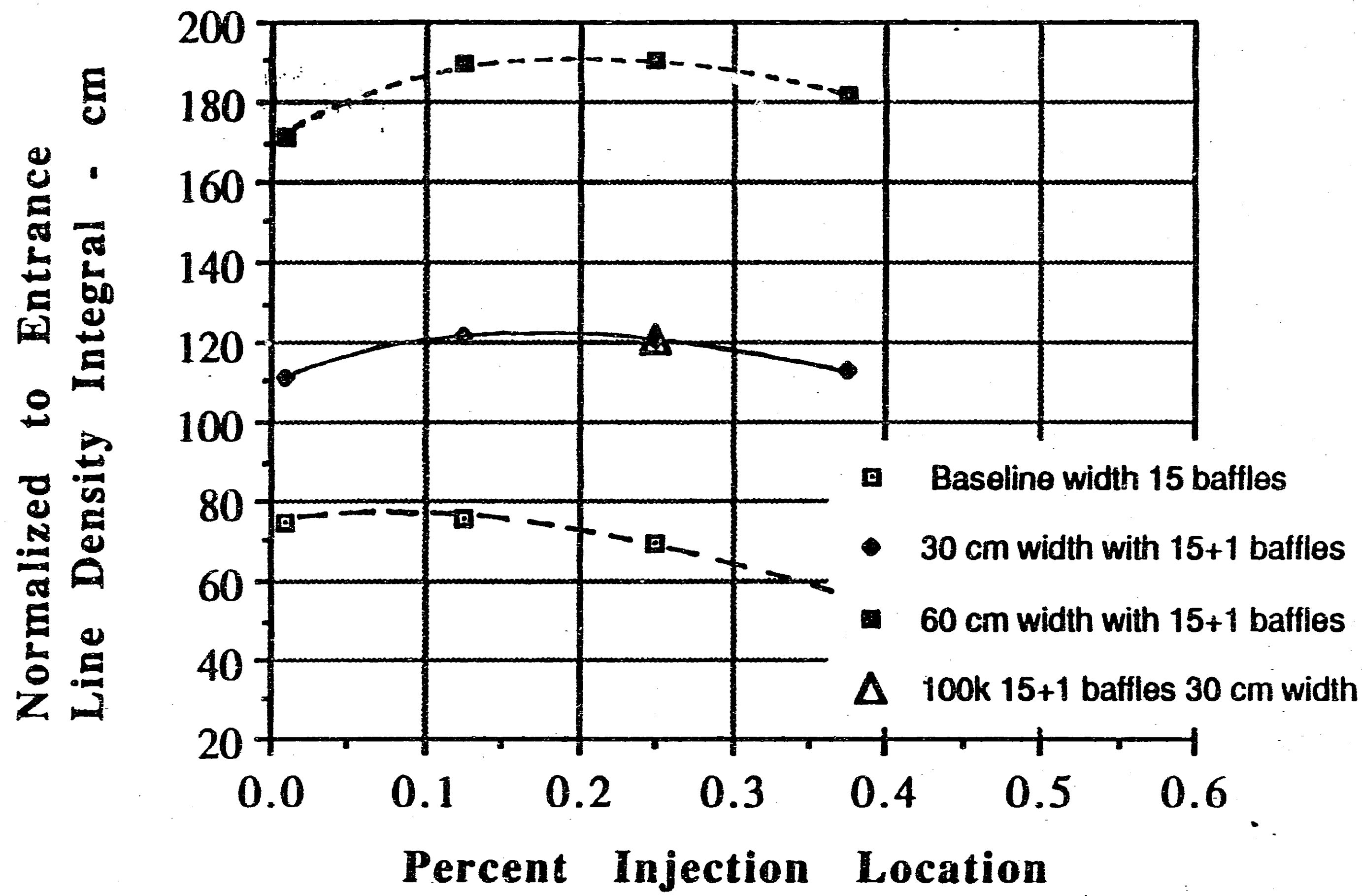
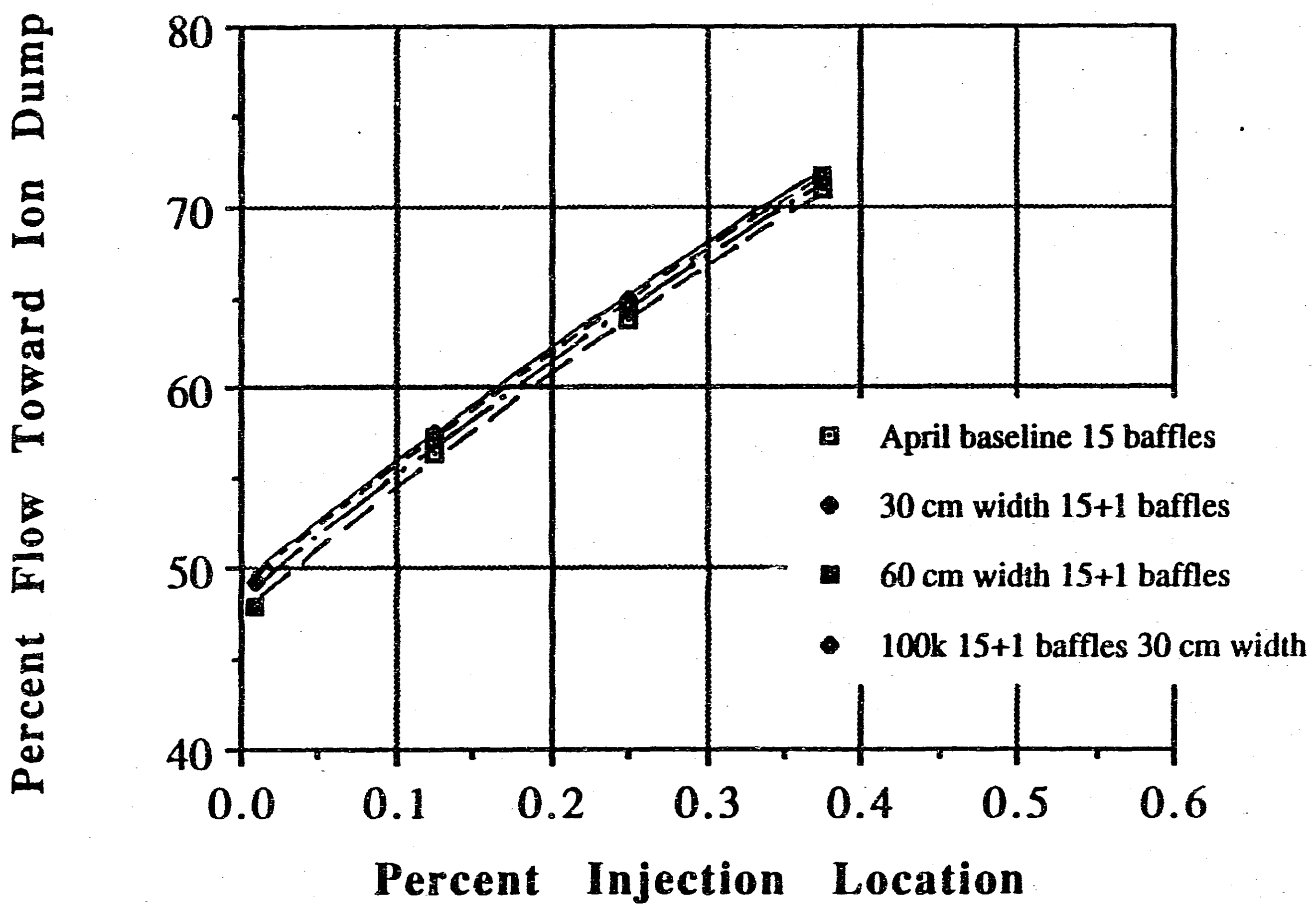


Figure 20 - Comparison of Width Effect on Ion Dump Gas Load



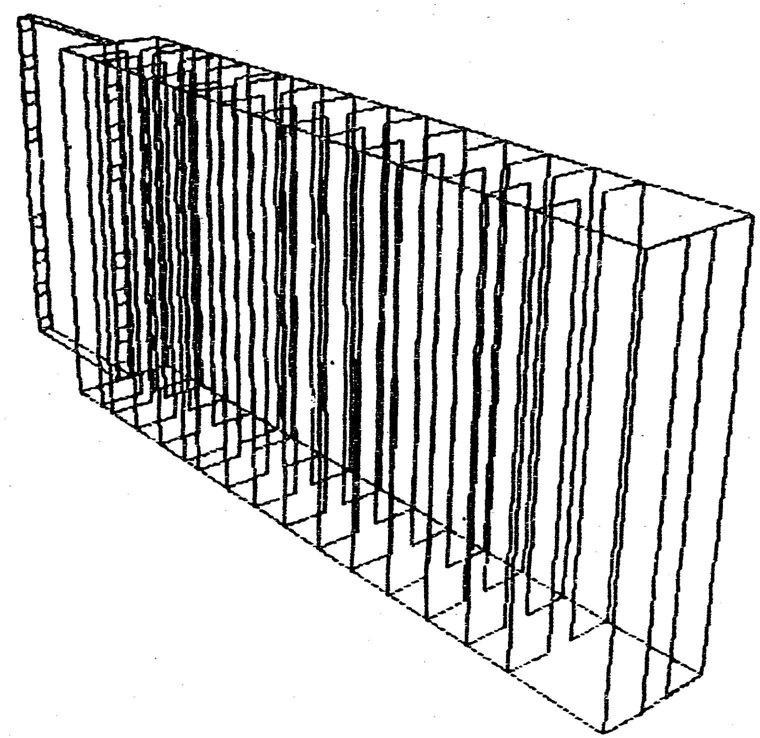


Figure 21 - Sketch of 60 cm wide neutralizer with 15 + 1 baffles

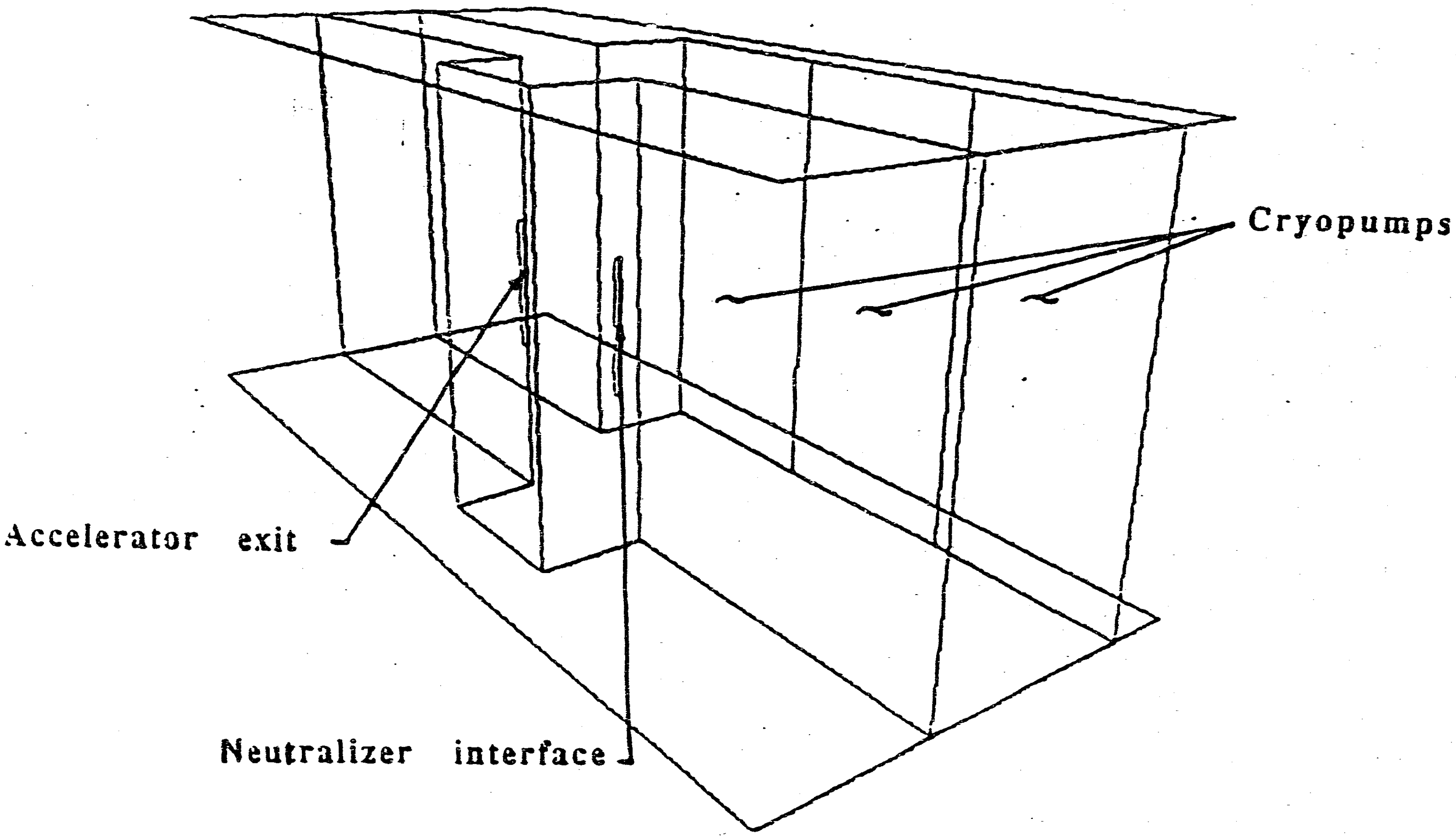
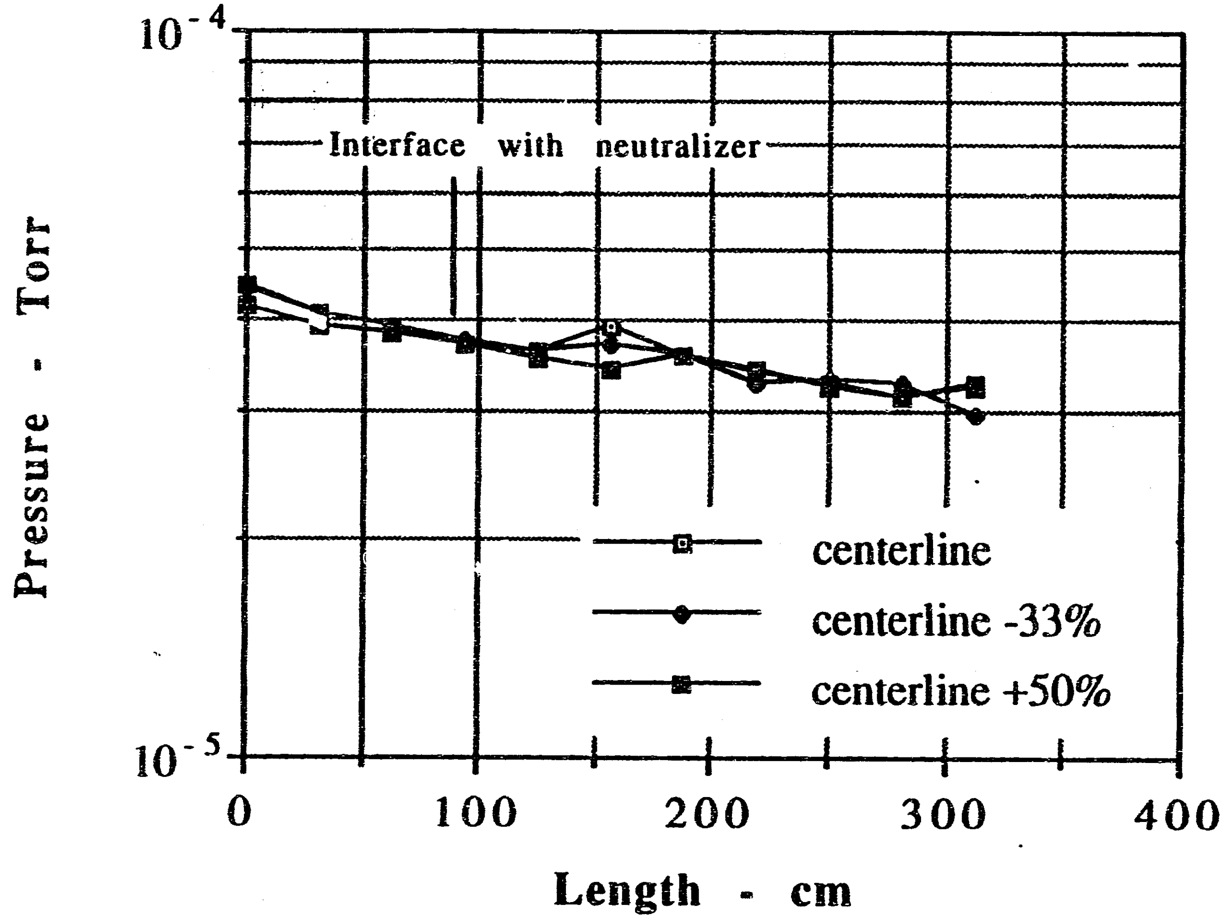


Figure 22 - GRAVE Accelerator compartment model

Figure 23 - Typical Pressure Variation on Accelerator Cryopump Face



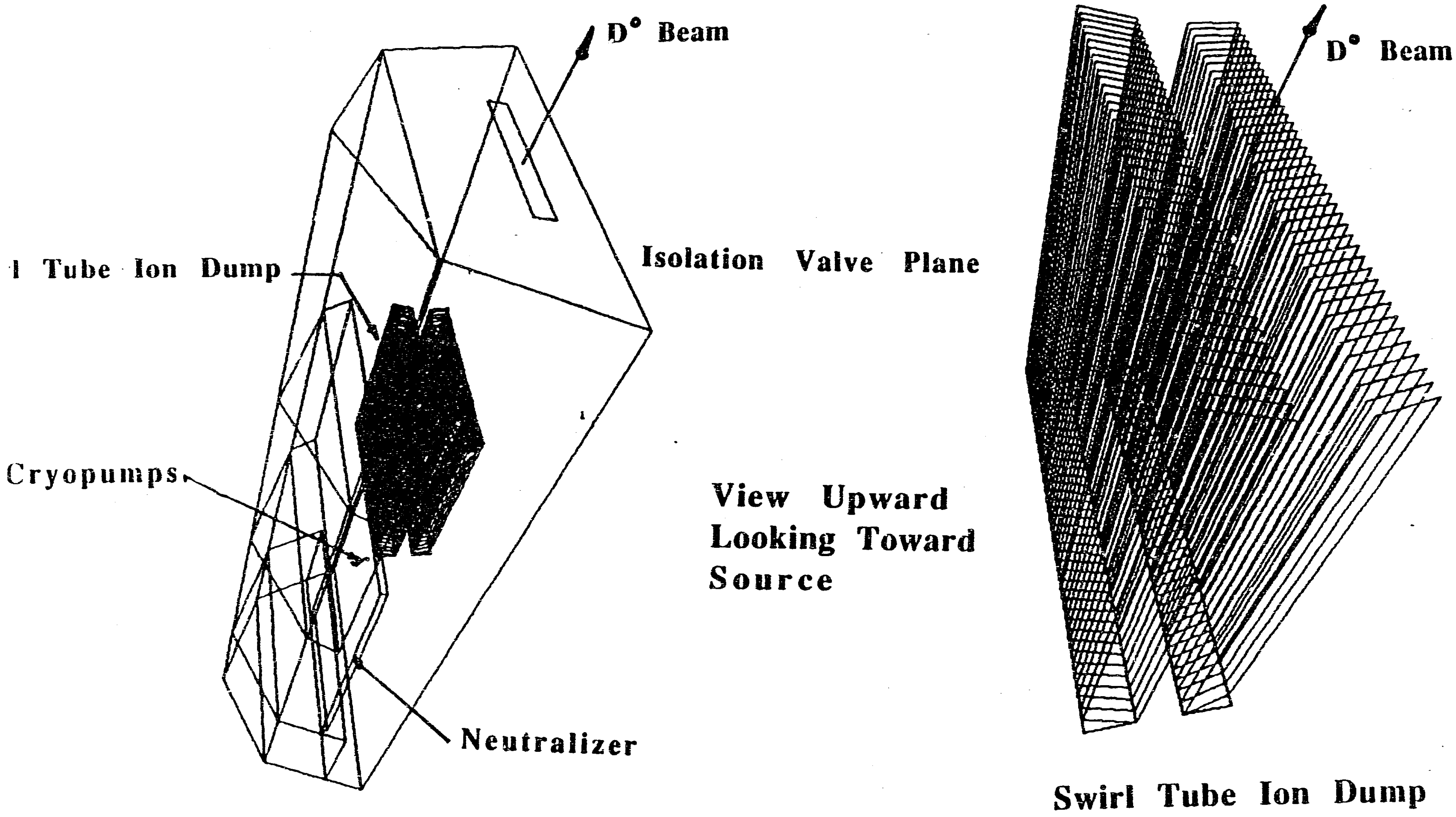
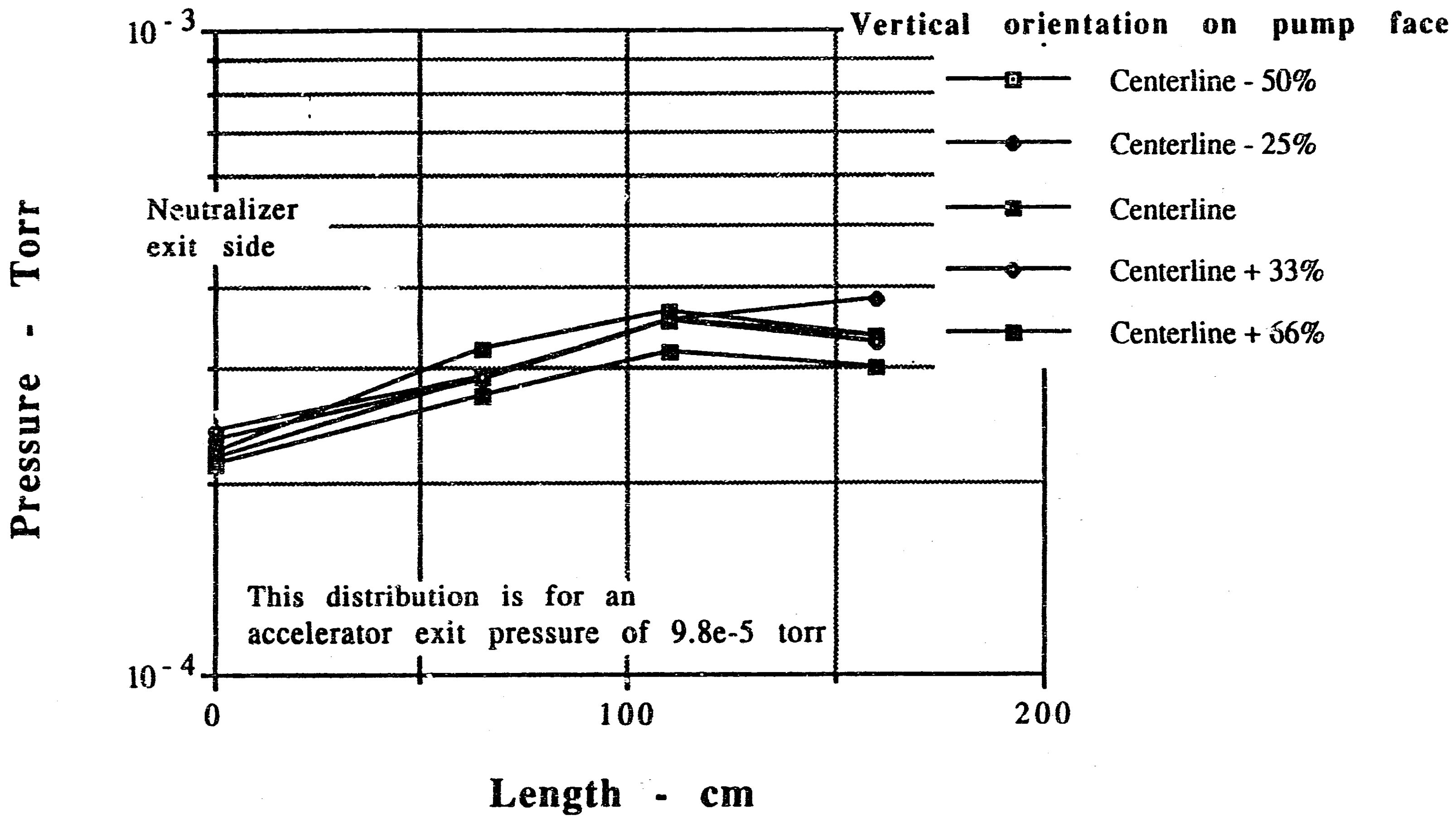


Figure 24 - GRAVE Ion Dump compartment model

Figure 25 - Typical Pressure Variation on Ion Dump Cryopump Face



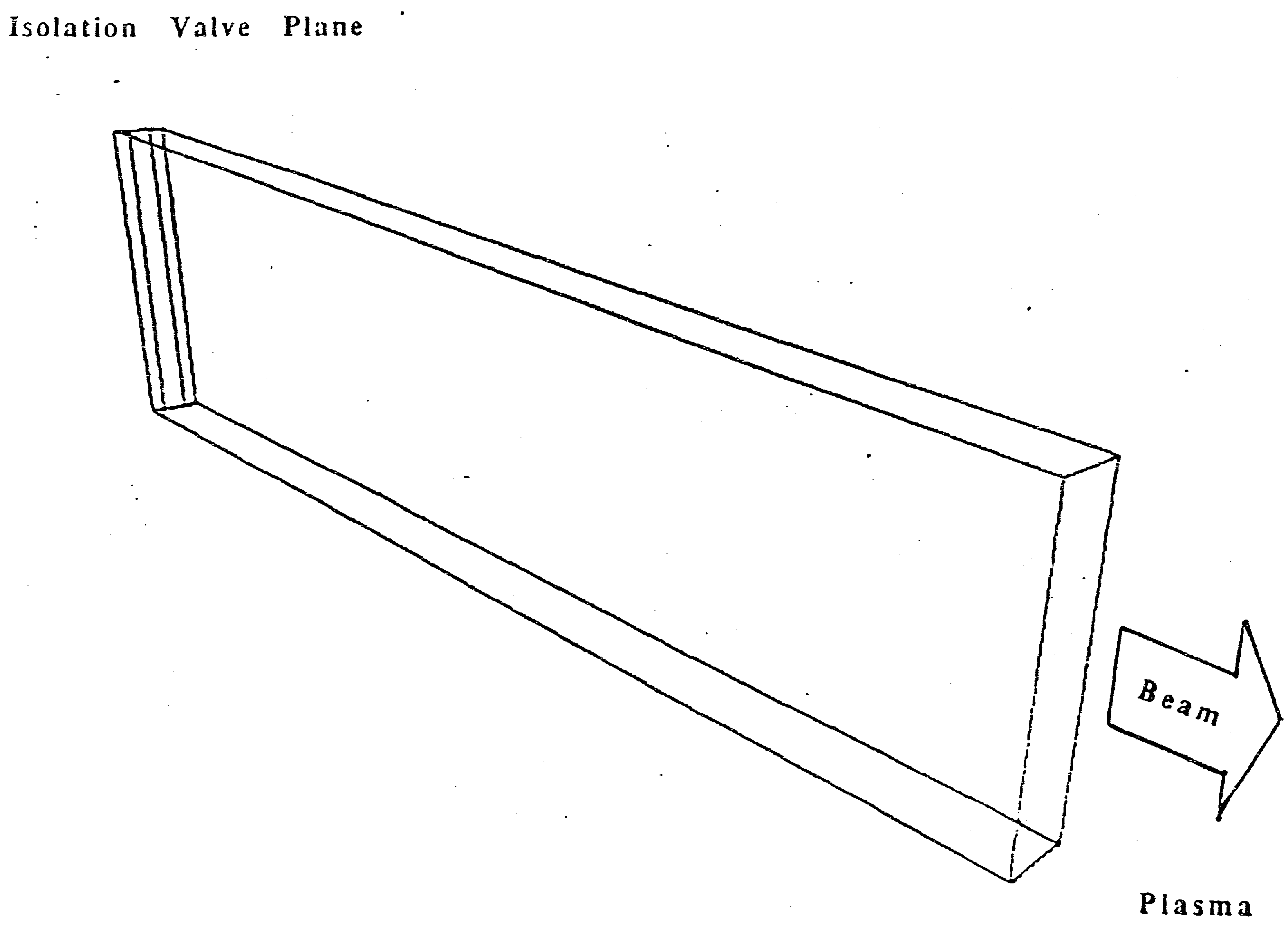
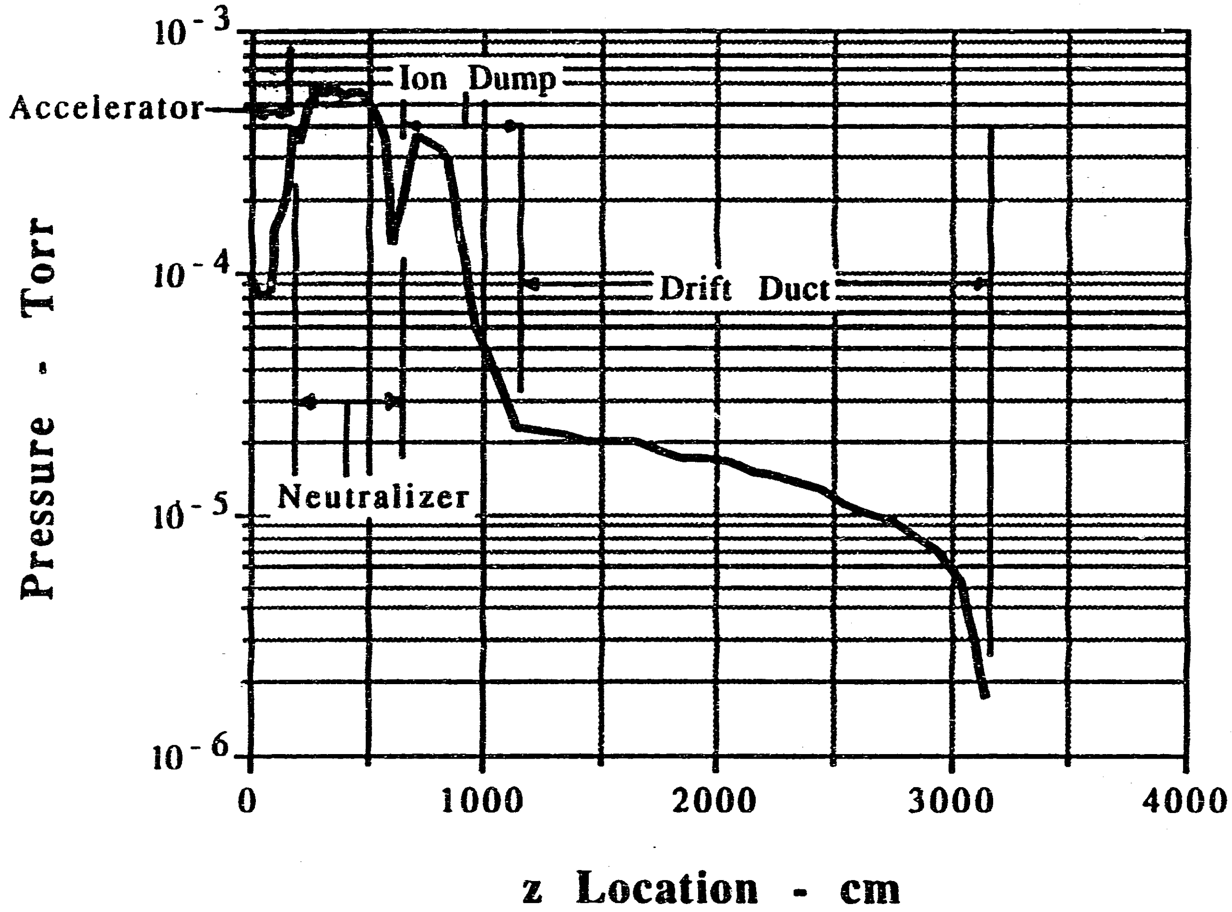


Figure 26 - GRAVE Drift Duct compartment model

Figure 27 - Beam Line Pressure Distribution



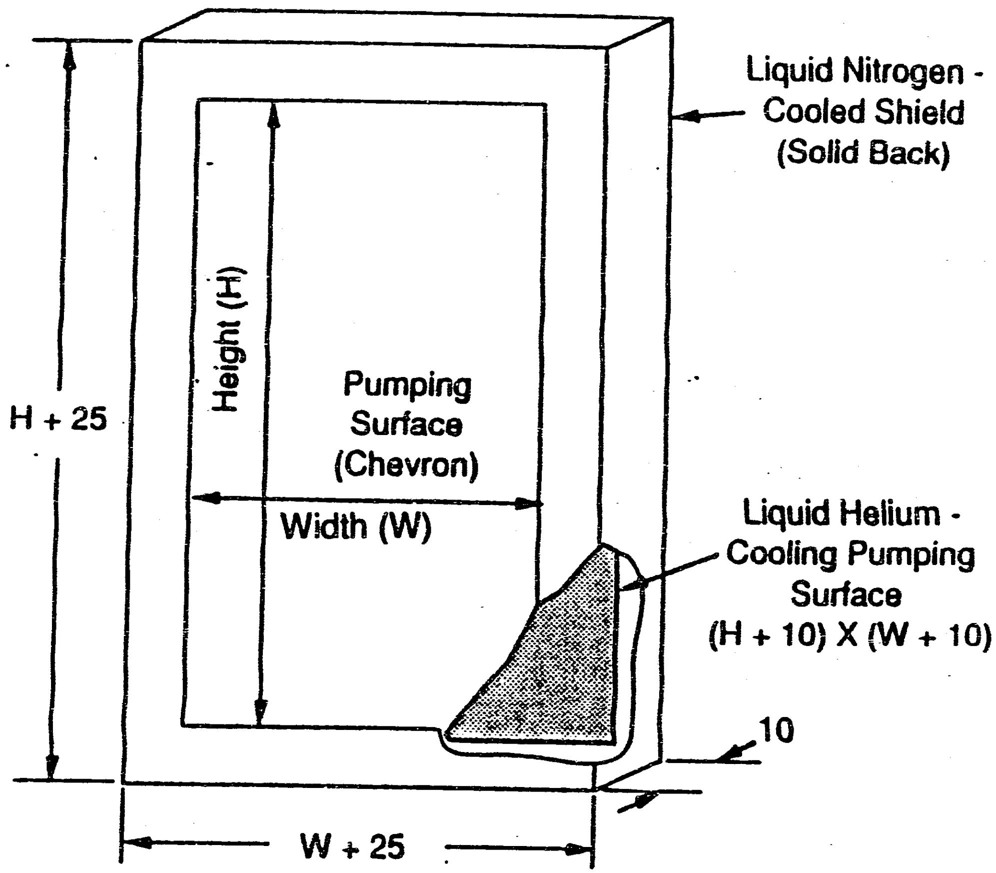


Figure 28 - Cryopump Model for Thermal Analysis

Event	Valve Open/Closed 1	2	3	4	5
Shutdown	C	C	O	C	C
Cooldown (Cldn) A	O	C	O	C	O
Cldn B/Circulate	O	O	C	C	O
Regenerate A	C	O	C	O	O
Regenerate B	C	C	O	O	O
Warmup	O	C	C	C	C

NOTES:
- *Opening of Valve 5 is controlled by level probe
- *Condition "A" is when vent temp is <15 K
- *Condition "B" is when vent temp is >15 K
- *Safety systems not shown

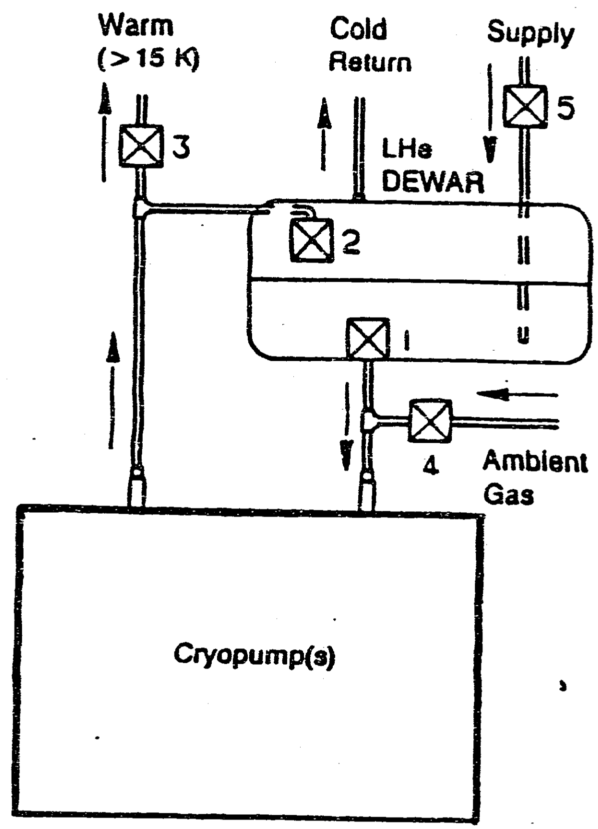


Figure 29-Typical Liquid Helium Distribution System for a Cryopump

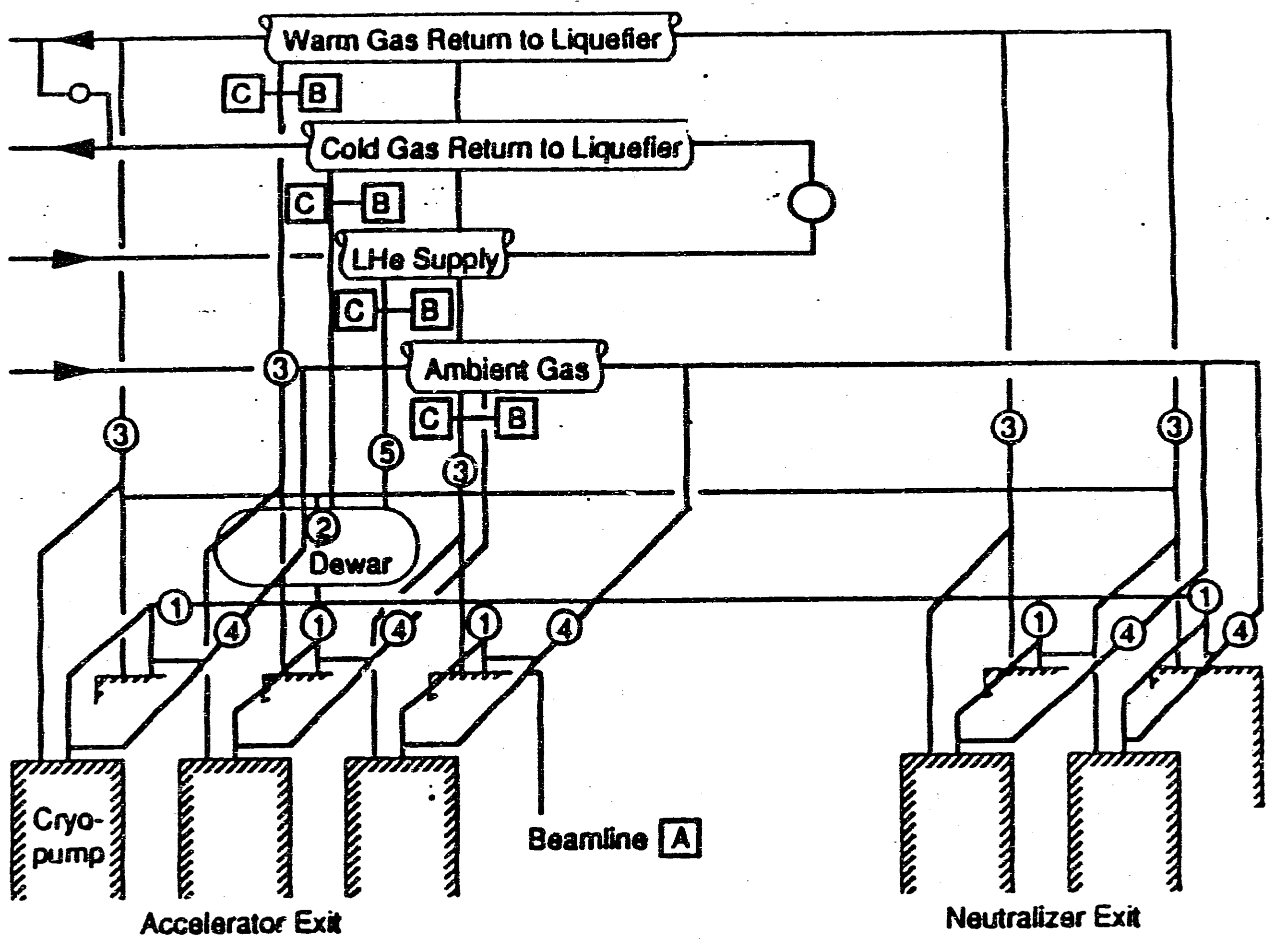


Figure 30-Helium Distribution for Beamline with Regenerable pumps

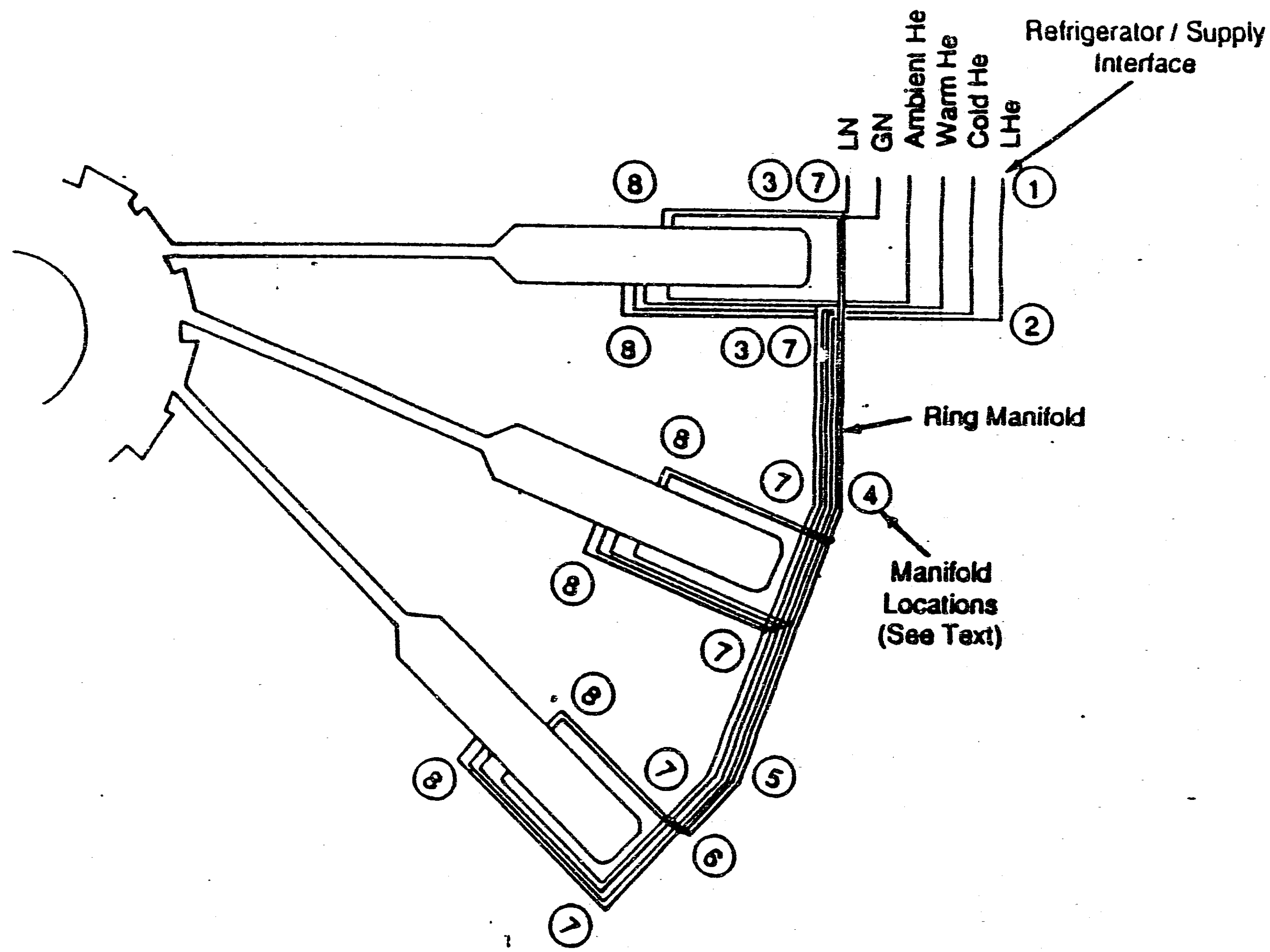


Figure 31-Cryogen Distribution System for Neutral Beam line System

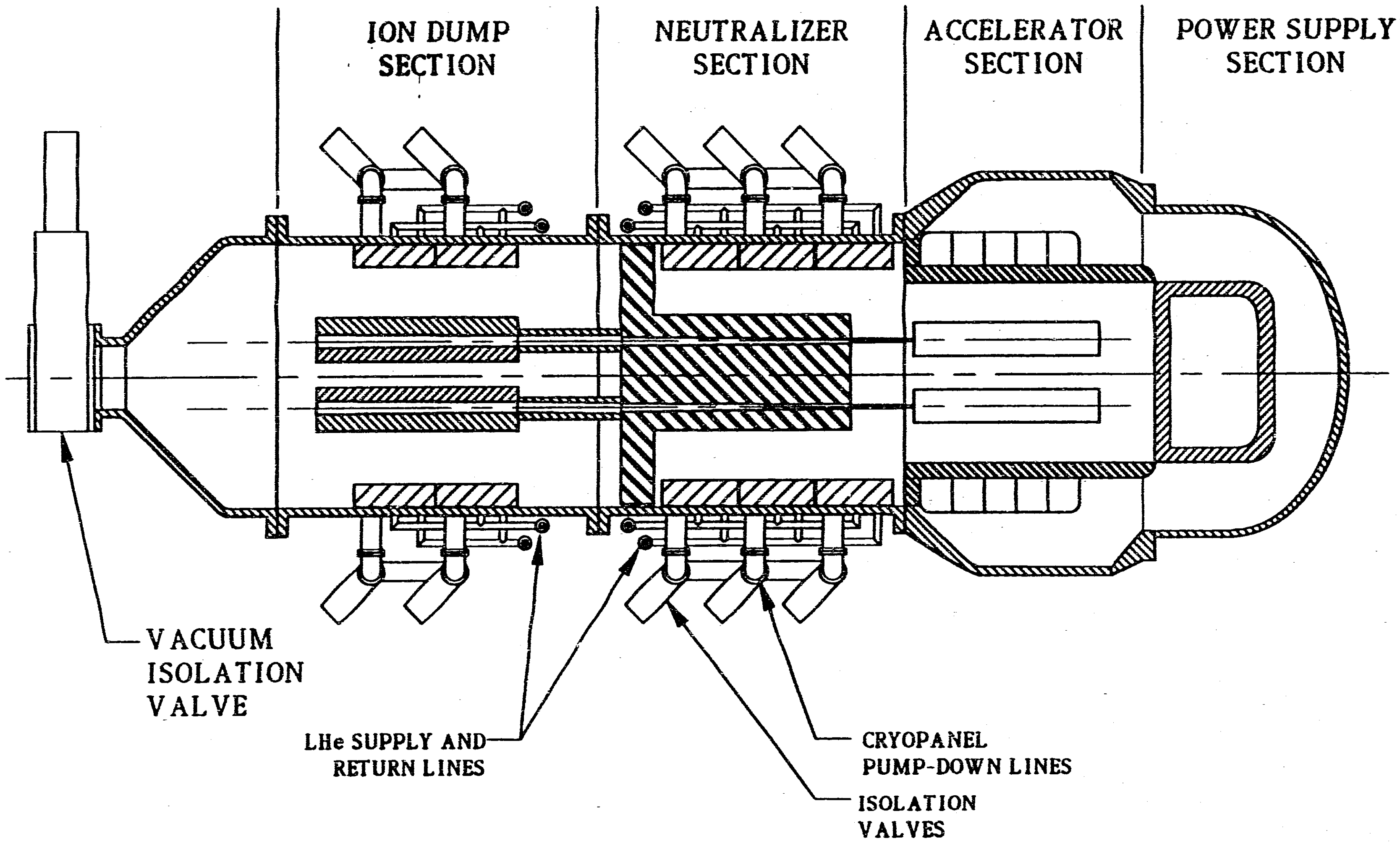


Figure 32 - Cutaway Schematic of Beam Line Module

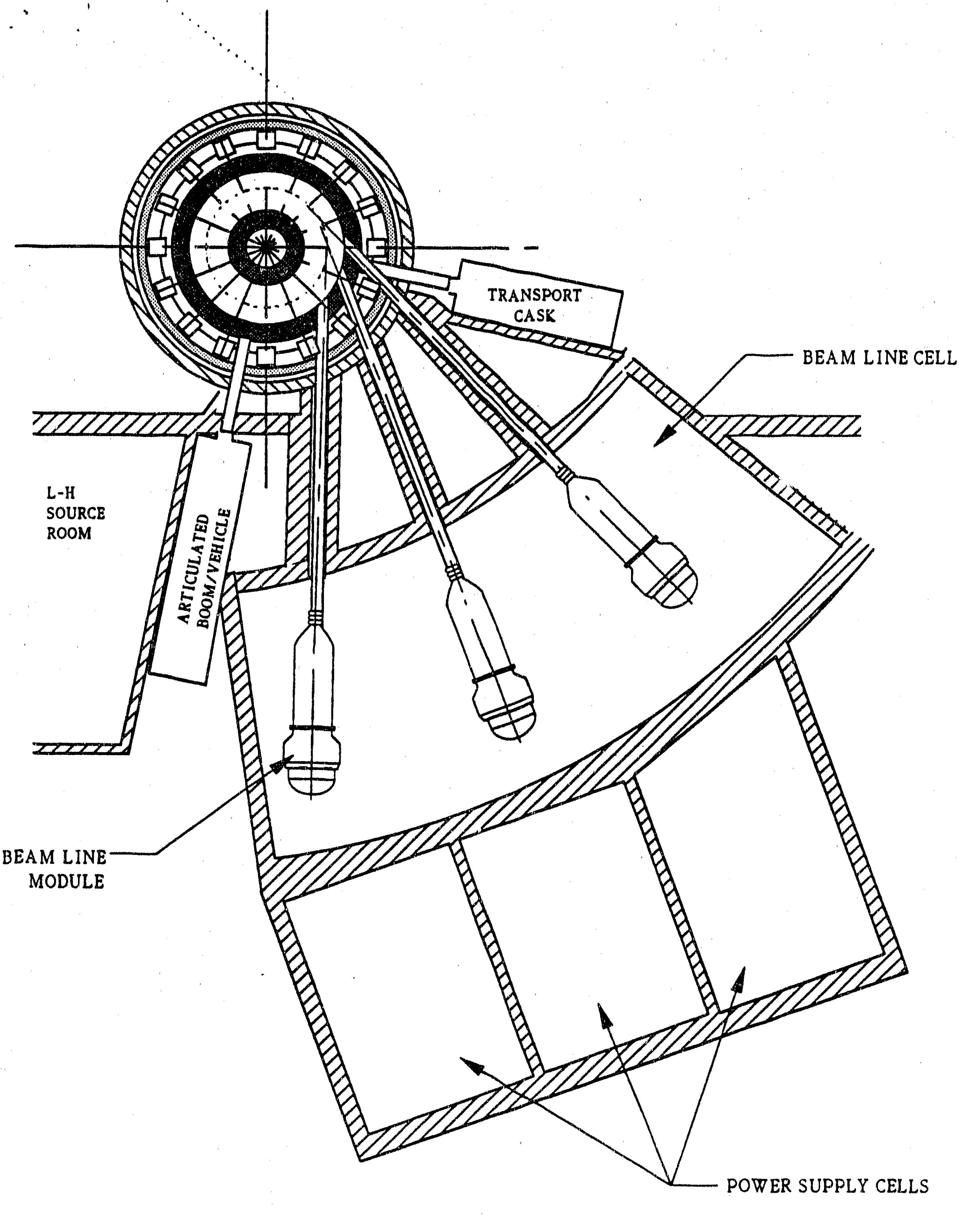


Figure 33 - Plan view of the Neutral Beam Line Arrangement for ITER

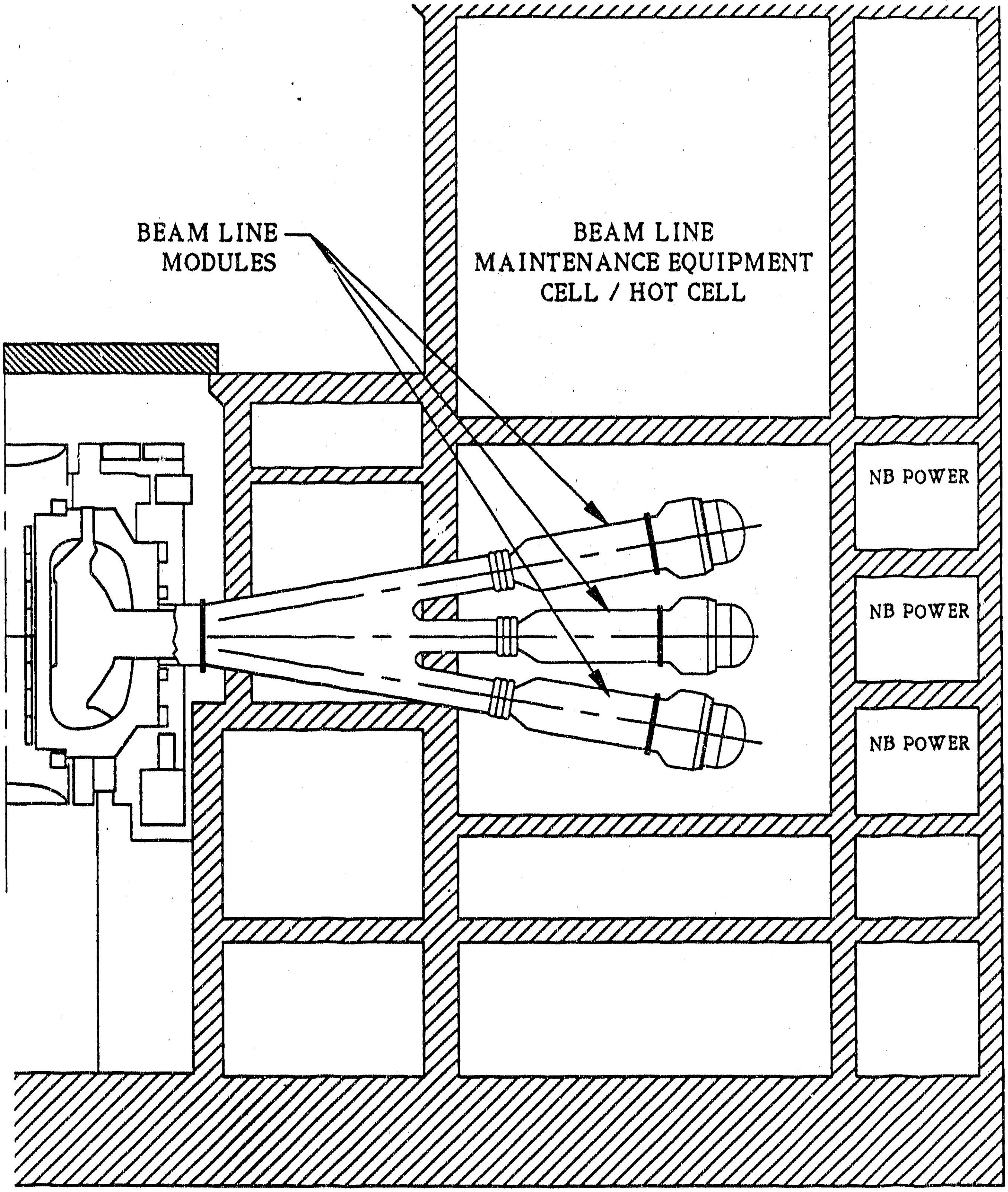


Figure 34 - Elevation view of the Neutral Beam Line for ITER

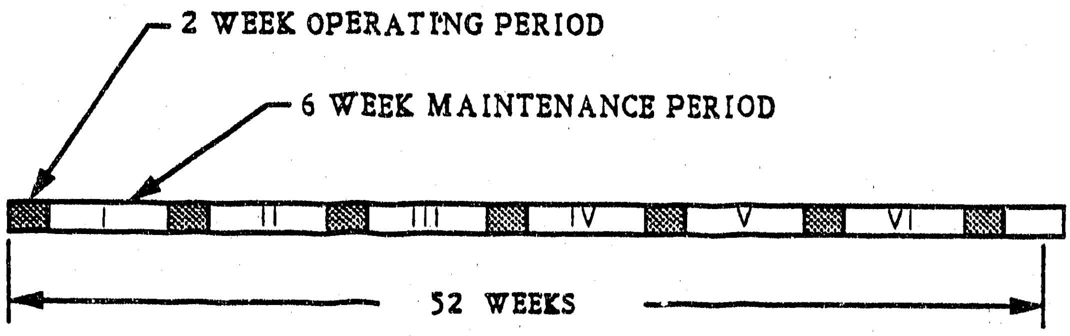


Figure 35. Schematic Arrangement of Annual Machine Operations and Maintenance Operation.

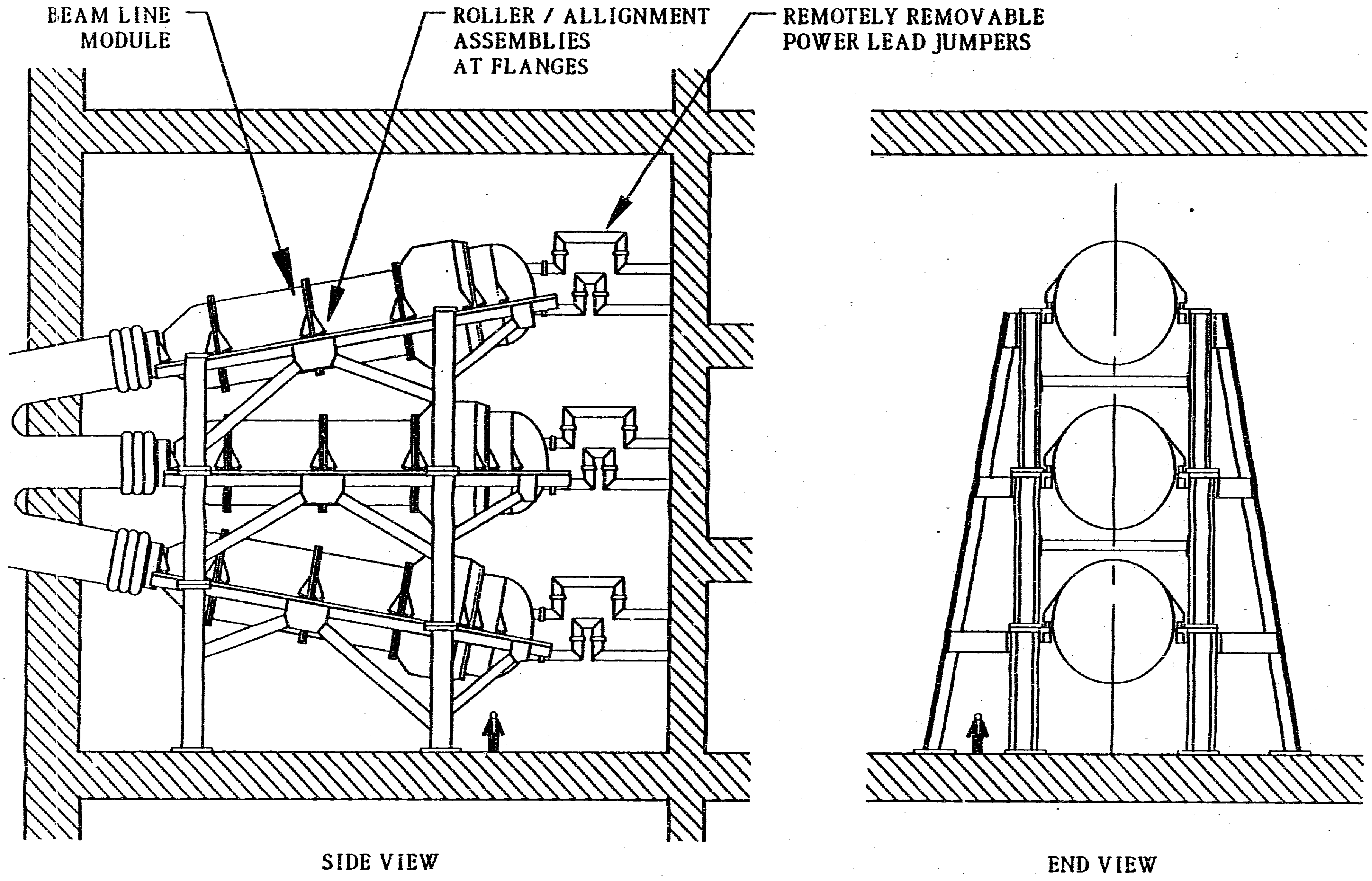


Figure 36 - Elevation view of NB cell with Support Structure

APPENDIX A

Evaluation of an Appendage Pump for Beamline Pumping

Reference 5 requested an evaluation of the use of appendage cryopumps in lieu of pumps placed directly within the beamline module. The apparent advantage is accessibility to the pumps for maintenance and replacement. This pump, like all appendage ·· .s, suffers from the conductance loss or conductance limitation naturally imposed by such an arrangement.

The details provided on the sketch in the reference were limited, but indicated a cylindrical compartment attached to the module wall, with a circular blocker door which could be stored at the aft (closed) end of the cylinder during operation, and could be moved on an axial actuator (plunger) to close the entrance for regeneration. The cylindrical surface is effectively the pumping surface. The end closure is not available for pumping because it is blocked by the door during operation.

Cryocondensation pumping of deuterium at pressures typically found in the beam line (in the 10^{-5} Torr range) requires a surface cooled below 20 K, typically a 4.2 K surface cooled by liquid or supercritical helium. Mandatory shielding of this surface (with 80 K chevrons or louvers) reduces pumping speed below ideal values for an unobstructed surface. The ideal capability of a cryopump with a chevron shield is reduced from 31.5 $1/sec\text{-}cm^2$ to 7.9 $1/sec\text{-}cm^2$. This is the value used to size in-vessel pumps; a 150,000 1/s pump would require a pumping surface (facing the source of the pumped gas) of 19000 cm^2 (equivalent to a 156 cm dia. circle).

With an appendage pump, the chevron- (or louver) shielded surface can be extended beyond the entrance (eg, as a cylinder) to attain the required pumping speed, provided that the entrance is not conductance limited. The major loss associated with this type of pump is the conductance loss into the cylindrical appendage. There will be a variation in molecular density in the canister from entrance to closed end. This effect dir...y affects the density of molecules that are presented to the cryopump surfaces at the po... along the cylinder making the back half of the pump much less effective than the front half. A

3-D pump model accounts for these effects.

The 3-D GRAVE code analysis of the pump design indicated on overall transmission probability of 0.68. The appendage pump geometry can incorporate a louver for thermal shielding of the pumping surface, compared to the use of chevrons required for the planor, in-vessel pumps.

The appendage pump louvers are arranged so that their effective openings are towards the closed, cooled end of the cylinder. The effectiveness of the pump thus includes the transmission probability of the louvers (0.32).

This value was obtained through successive GRAVE runs evaluating the way in which the particles progressed from entry to pump surface. Equating this to effective pump speed yields a value of 6.93 l/sec-cm^2. This value is about 12% less than the capability projected for an in-vessel pump.

On this basis the frontal area allocated to the in-vessel cryopumps in the accelerator exit cavity and the ion dump cavity would have to be increased by 14% to accommodate the appendage pumps. The requirement for actuator mechanisms at the pump entrance can further reduce the pump's entrance transmissivity and must be considered when they are defined.

APPENDIX B

Compilation of 1990 FAX Transmittals

From P. Purgalis:

1. Dated 3-8-90
2. Dated 3-26-90
3. Dated 4-5-90
4. Dated 5-8-90
5. Dated 5-9-90
6. Dated 8-10-90

Lawrence Berkeley Laboratory
1 Cyclotron Road Berkeley, California 94720
(415) 486-4000 • FTS 451-4000

COVER SHEET

DATE: 3-8-90

TO: DOUG SEDGLEY FAX No (516) 575-~~5023~~ 6619

GRUMMAN SPACE SYSTEMS VERIFY (516) 575-8669

B29-25

BEAMDUMP ELEVATION

" PLAN

CRYOPUMP OPTION

FROM:

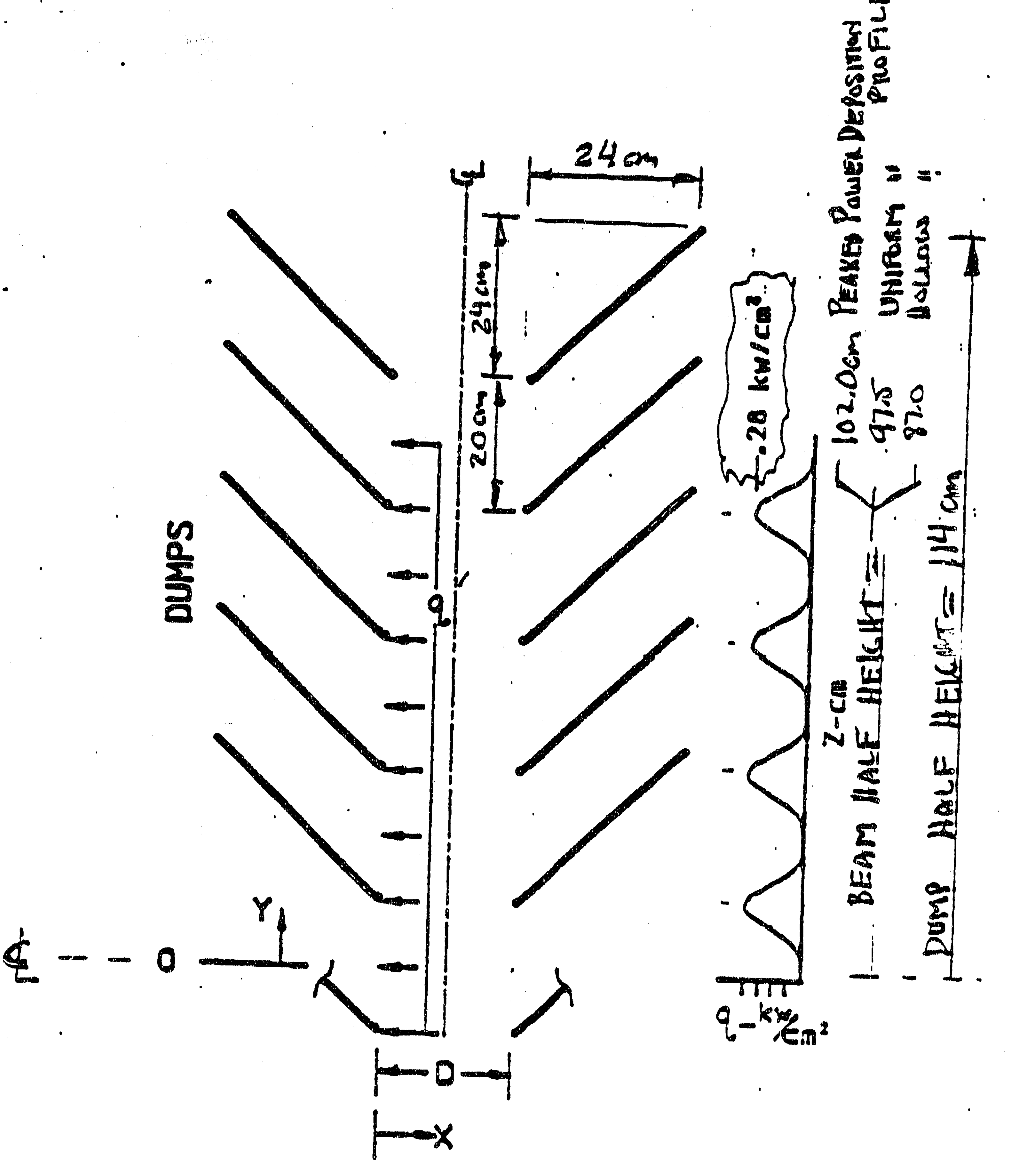
PETER PURGALIS

NUMBER OF PAGES 3 (PLUS COVER SHEET)

TELECOPIER INFORMATION:

Copier Number: (415) 486-5105 – FTS 451-5105
Verify Number: (415) 486-5011 – FTS 451-5011

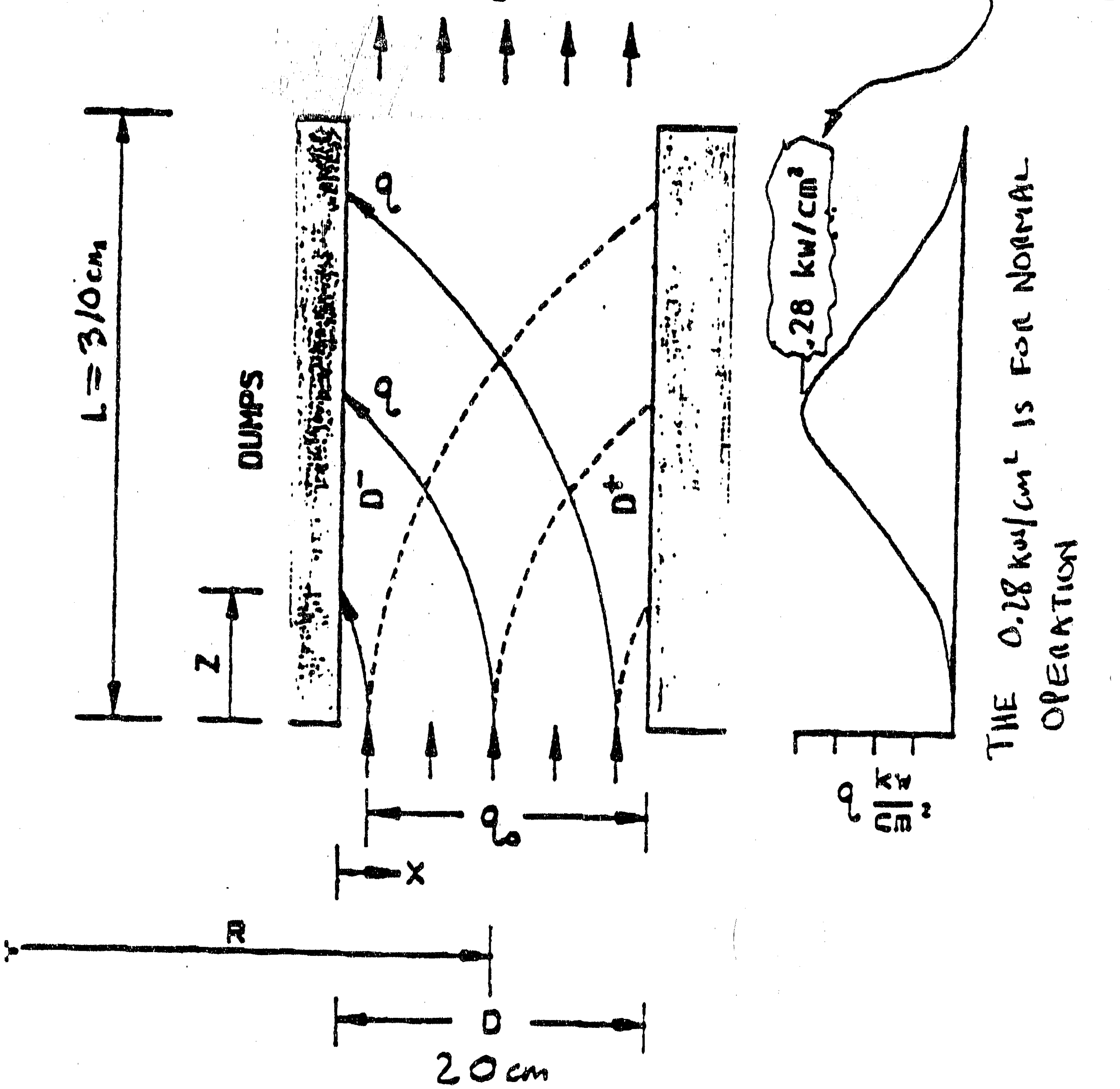
Xerox 295 Unattended Automatic Machine (24 hours)



ELECTROMAGNETIC DEFLECTOR AND BEAMDUMPS
ELEVATION VIEW

3-7-90

DURING COMMISSIONING, WHEN WE DO NOT WANT BEAM TO GO INTO TOKAMAK, THE NEUTRALIZER IS OPERATED WITHOUT GAS AND ALL OF THE BEAM (D^-) IS DEFLECTED IN TO ONE ION DUMP, THE PEAK HEAT FLUX IS 1.4 kW/cm AT THE LEADING EDGE OF THE DUMP.



ELECTROMAGNETIC DEFLECTOR AND BEAMDUMPS
PLAN VIEW

3-7-90

PLEASE CHECK TO SEE IF WE COULD USE THIS ~~[illegible]~~ TYPE OF REGENERABLE CRYOPUMPS. THIS IS TAKEN FROM USSR PROPOSAL
3-7-90

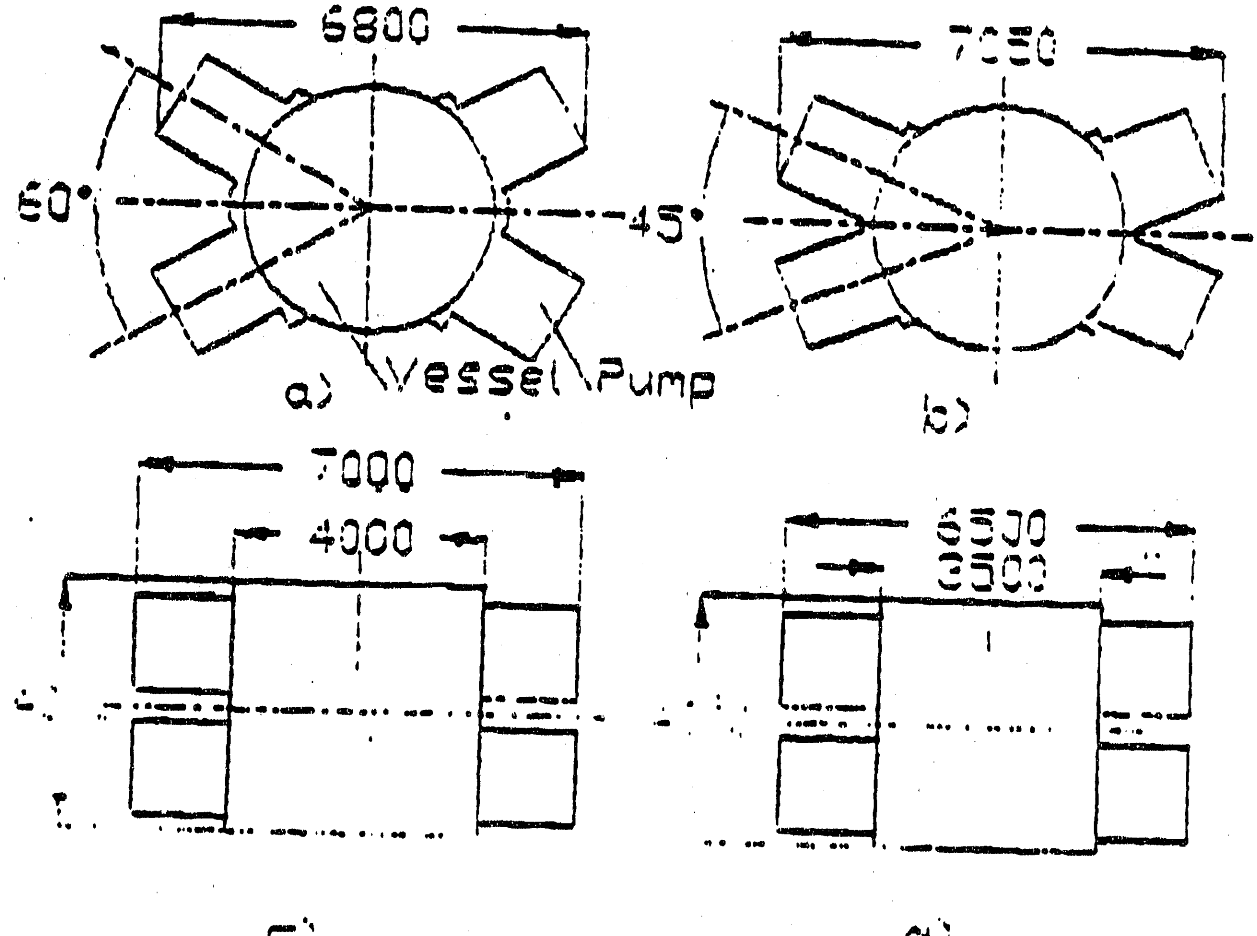
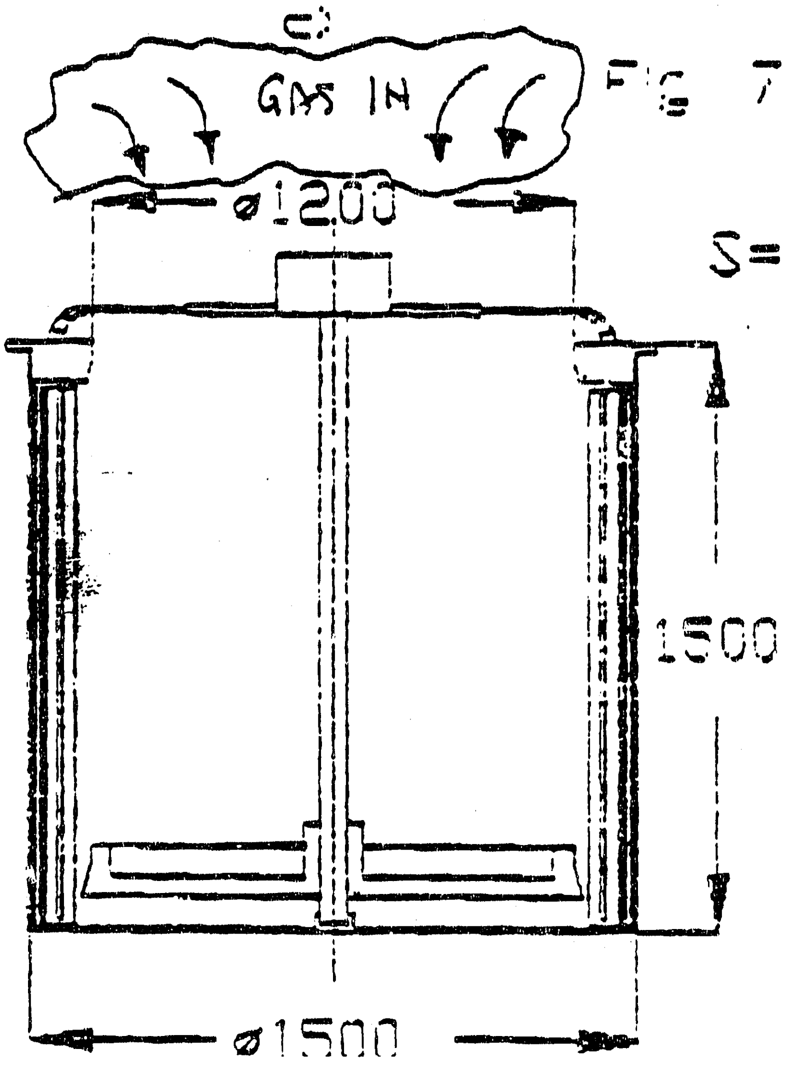


Fig 7



S=150,000 l/s (D2)

Fig 8

Lawrence Berkeley Laboratory
1 Cyclotron Road Berkeley, California 94720
(415) 486-4000 • FTS 451-4000

COVER SHEET

DATE: 3-26-90

TO: DOUG SEDGLEY FAX No (516) 575-6619
GRUMMAN SPACE SYSTEMS VERIFY (516) 575-8669
B29-25

FROM:

PETER PURGALIS

NUMBER OF PAGES 8 (PLUS COVER SHEET)

TELECOPIER INFORMATION:

Copier Number: (415) 486-5105 – FTS 451-5105
Verify Number: (415) 486-5011 – FTS 451-5011

Xerox 295 Unattended Automatic Machine (24 hours)

3/23/90

US ITER BEAMLINE PARAMETERS

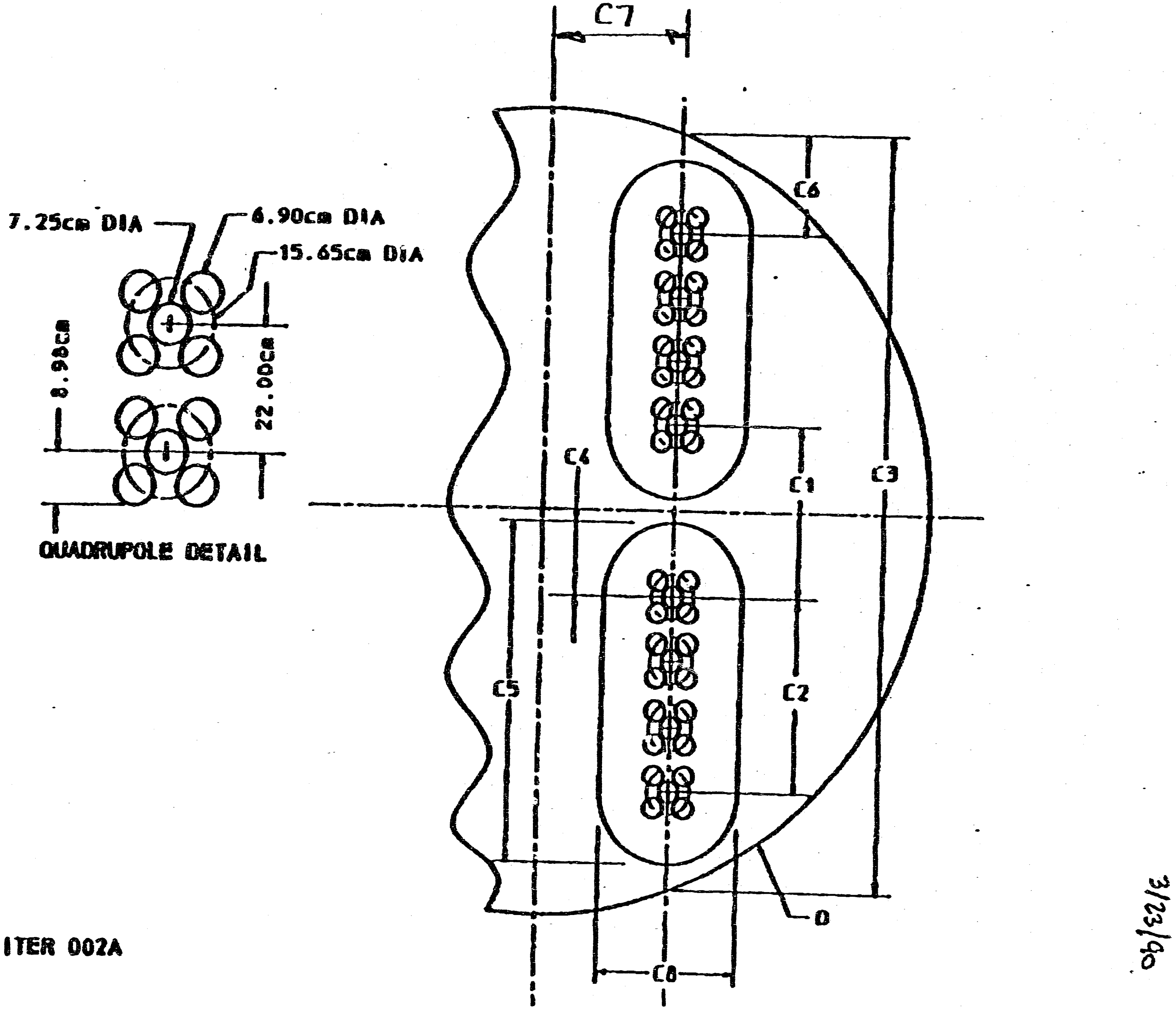
INPUT DATA file: Iter/1A-- Iter 1.3Mev 2/20/90

Total no of modules	(nbline)	=	9
Total delivered power	(topwr)	=	90.00 Mw
Energy	(energy)	=	1.30 MV
Accelerator output/channel	(bamps)	=	0.88 Amps
Neutralizer efficiency	(efneut)	=	0.61
Transmission efficiency	(eftrans)	=	0.97
Reionization loss	(rilos)	=	0.05
Module diameter	(bmld)	=	400.00 cm
Module spacing cntr-cntr	(dctr)	=	650.00 cm
No of arrays per module	(naray)	=	2
Array spacing horizontal	(araysh)	=	47.50 cm [c7]
Array width	(arayw)	=	50.00 cm [c8]
Beam diameter at accel exit	(dbmlt)	=	6.00 cm
Channel spacing	(sbmlt)	=	22.00 cm
No of sources/array	(nseg)	=	2
Spacing betwn seg hole-hole	(sseg)	=	58.00 cm [c1]
Dist last hole to segmnt end	(dseg)	=	25.00 cm [c4]
Dist segment to insulator	(siseg)	=	34.00 cm [c6]

CALCULATED DATA

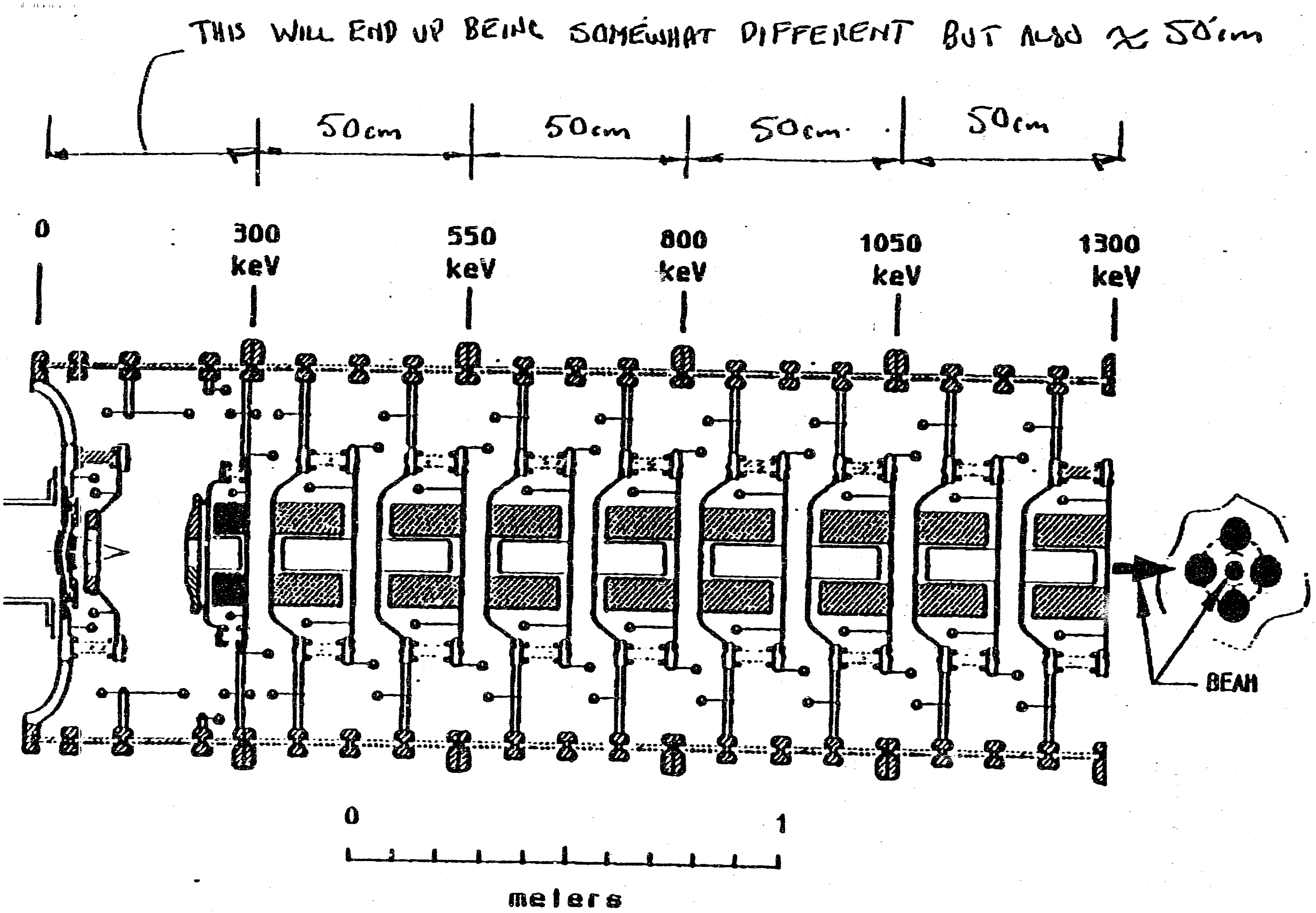
Delivered power/module req	(topwrb)	=	10.00 Mw
Channels/module-as calculated	(bmltn)	=	15.50
Channels/source-nearest no	(bmltsps)	=	4
Delivered power/module actual	(apwrb)	=	10.29 Mw
Delivered current/module	(curpbln)	=	7.92 Amps
Segment height hole ctr-cntr	(segh)	=	66.00 cm [c2]
Overall segment height	(osegh)	=	116.00 cm [c5]
Array height	(arayh1)	=	258.00 cm [c3]
Diameter of insulator	(dins)	=	274.94 cm [D]

Numbers enclosed in [ ] refer to Sketch ITER 002



C7
C6
C3
C1
C2
C4
C5
C8
D
7.25cm DIA
6.90cm DIA
15.65cm DIA
8.98cm
22.00cm
QUADRUPOLE DETAIL
3/23/90

ITER 002A



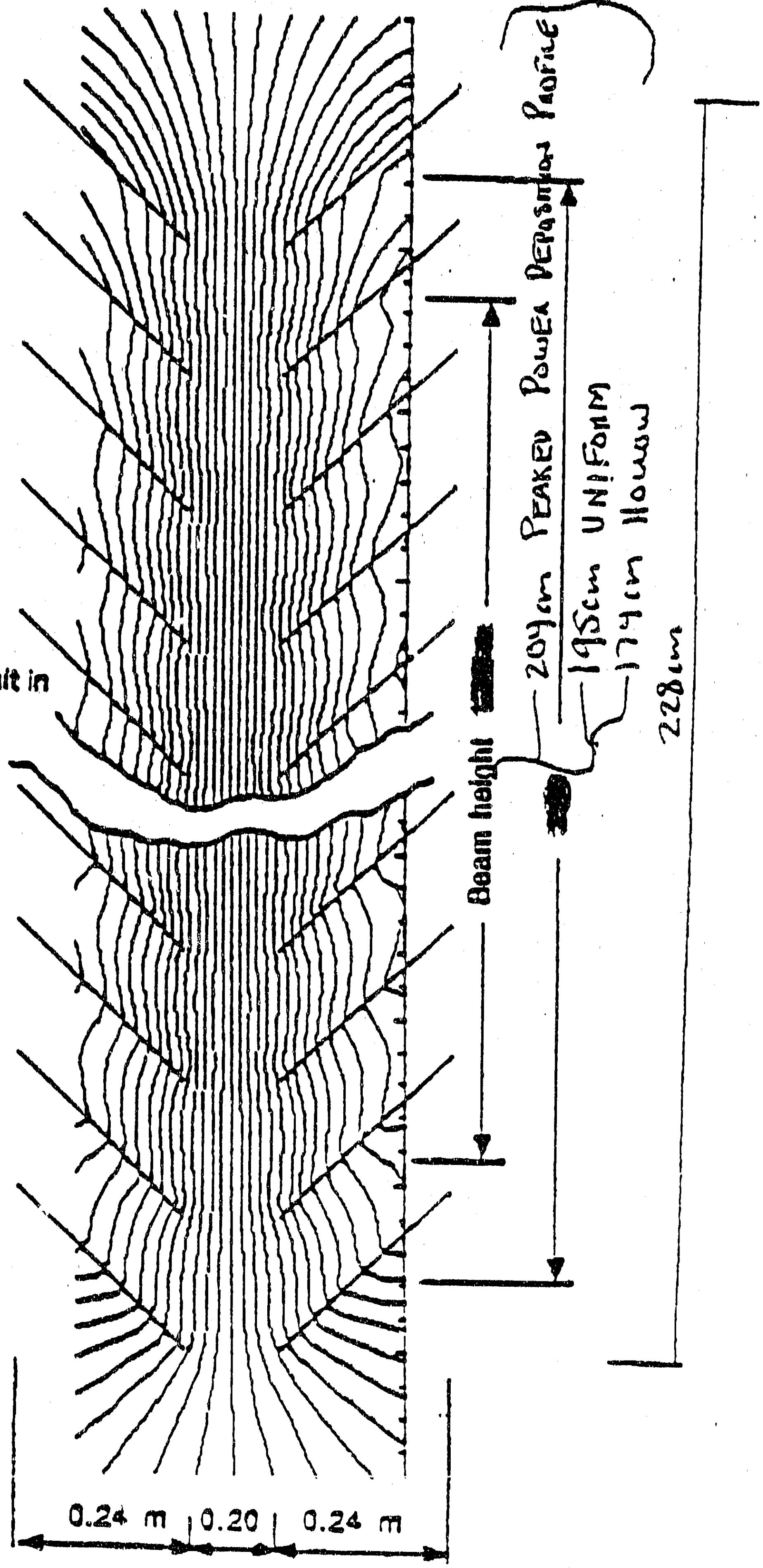
1 Ampere, 1.3 MeV ESQ Accelerator
SINGLE CHANNEL SHOWN

3/23/90

SAME AS 3-7-90 BUT COULD CHANGE SOME WHAT.

3/23/9

ELECTROMAGNETIC DEFLECTOR AND BEAM DUMPS



per meter or a total of 20 kA result in B = 100 Gauss in the 0.20 m gap

3/23/90

file: iter/dm/lblaix { HEAT FLUX ON DUMPS DURING COMMISSIONING
i = .88 AMPS/CHANNEL @ ACCELERATOR EXIT, NO GAS IN NEUTRALIZER,
DURING NORMAL OPERATION HEAT FLUX IS 20% OF VALUES SHOWN

title: iter beam dump study, center module only, one array, 3-23-90

Atomic mass no = 2 ion = D
Beam energy (u) = 1.30 Mev
B field at dumps = 100.00 Gauss — SEE FIG 1
Ion path radius = 23.21 m Velocity = 0.1120E+08 m/s
Distance between dumps = 20.00 cm
Distance accel to dumps = 6.00 m

Z = DISTANCE FROM START OF DUMPS (FIG 1) AT WHICH q = HEAT FLUX ON LEADING EDGE OF DUMPS.

Z (cm)	=	.00	96.34	136.22	166.79	192.55	215.24	235.73	254.56	272.08	288.52	304.06
ANGL (deg)	=	.00	2.38	3.36	4.12	4.76	5.32	5.83	6.30	6.73	7.14	7.53
Sin(A)	=	.00	.04	.06	.07	.08	.09	.10	.11	.12	.12	.13

VERTICAL DISTANCE

Y(cm) - q/qo kw/cm2

Y (cm)												
.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	q
	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	q_o
2.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	q
	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	q_o
4.00	.00	.00	.00	.00	0.00	0.00	0.00	.00	.00	.00	.00	q
	.00	.00	.00	.00	.01	.01	.01	.00	.00	.00	.00	q_o
6.00	.00	.00	0.00	0.00	0.00	.01	.01	0.00	0.00	.00	.00	q
	.00	.00	.01	.03	.06	.08	.06	.03	.01	.00	.00	q_o
8.00	.00	.00	0.00	.01	.04	.05	.04	.02	0.00	.00	.00	q
	.00	.00	.04	.19	.43	.55	.43	.19	.04	.00	.00	q_o
10.00	.00	0.00	.01	.06	.17	.23	.20	.10	.02	0.00	.00	
	.00	.02	.18	.88	1.99	2.53	1.99	.88	.18	.02	.00	
12.00	.00	0.00	.03	.19	.50	.71	.61	.29	.06	.01	.00	
	.00	.05	.54	2.66	6.05	7.67	6.05	2.66	.54	.05	.00	
14.00	.00	0.00	.06	.39	1.01	1.43	1.24	.59	.13	.01	.00	
	.00	.09	1.10	5.37	12.19	15.46	12.19	5.37	1.10	.09	.00	
16.00	.00	0.00	.09	.52	1.36	1.93	1.67	.79	.17	.01	.00	
	.00	.12	1.48	7.24	16.43	20.34	16.43	7.24	1.48	.12	.00	
18.00	.00	0.00	.08	.47	1.23	1.75	1.51	.72	.16	.01	.00	
	.00	.11	1.34	6.55	14.87	18.35	14.87	6.55	1.34	.11	.00	
20.00	.00	0.00	.05	.29	.75	1.36	.91	.44	.09	.01	.00	
	.00	.07	.81	3.97	9.01	11.43	9.01	3.97	.81	.07	.00	
22.00	.00	0.00	.02	.11	.30	.43	.37	.18	.04	0.00	.00	
	.00	.03	.33	1.60	3.64	4.62	3.64	1.60	.33	.03	.00	
24.00	.00	0.00	.01	.03	.08	.11	.10	.05	.01	0.00	.00	
	.00	.01	.09	.43	.97	1.23	.97	.43	.09	.01	.00	
26.00	.00	.00	0.00	.01	.01	.02	.02	.01	0.00	.00	.00	
	.00	.00	.02	.08	.18	.22	.18	.08	.02	.00	.00	
28.00	.00	.00	0.00	0.00	.01	.01	.01	0.00	0.00	.00	.00	
	.00	.00	.01	.04	.08	.10	.08	.04	.01	.00	.00	
30.00	.00	.00	0.00	.01	.04	.05	.04	.02	0.00	.00	.00	
	.00	.00	.04	.19	.44	.56	.44	.19	.04	.00	.00	
32.00	.00	0.00	.01	.06	.17	.24	.20	.10	.02	0.00	.00	
	.00	.02	.18	.38	2.01	2.55	2.01	.88	.18	.02	.00	
34.00	.00	0.00	.03	.19	.50	.71	.62	.29	.06	.01	.00	
	.00	.05	.55	2.68	6.08	7.71	6.08	2.68	.55	.05	.00	
36.00	.00	0.00	.06	.39	1.01	1.44	1.24	.59	.13	.01	.00	
	.00	.09	1.10	5.38	12.23	15.51	12.23	5.38	1.10	.09	.00	
38.00	.00	0.00	.09	.52	1.36	1.93	1.67	.79	.17	.01	.00	

3/23/9?

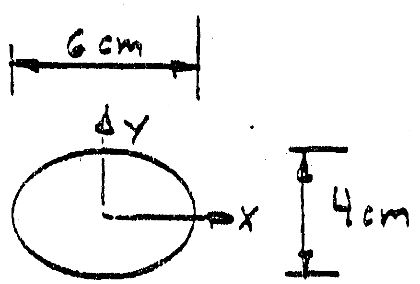
	.00	.12	1.48	7.24	16.44	20.85	16.44	7.24	1.48	.12	.00
40.00	.00	0.00	.08	.47	1.23	1.75	1.51	.72	.16	.01	.00
	.00	.11	1.34	6.53	14.84	18.82	14.84	6.53	1.34	.11	.00
42.00	.00	0.00	.05	.28	.74	1.06	.91	.43	.09	.01	.00
	.00	.07	.81	3.95	8.98	11.38	8.98	3.95	.81	.07	.00
44.00	.00	0.00	.02	.11	.30	.43	.37	.17	.04	0.00	.00
	.00	.03	.33	1.59	3.62	4.59	3.62	1.59	.33	.03	.00
46.00	.00	0.00	.01	.03	.08	.11	.10	.05	.01	0.00	.00
	.00	.01	.09	.42	.96	1.22	.96	.42	.09	.01	.00
48.00	.00	.00	0.00	.01	.01	.02	.02	.01	0.00	.00	.00
	.00	.00	.02	.08	.17	.22	.17	.08	.02	.00	.00
50.00	.00	.00	0.00	0.00	.01	.01	.01	0.00	0.00	.00	.00
	.00	.00	.01	.04	.08	.10	.08	.04	.01	.00	.00
52.00	.00	.00	0.00	.01	.04	.05	.04	.02	0.00	.00	.00
	.00	.00	.04	.19	.44	.56	.44	.19	.04	.00	.00
54.00	.00	0.00	.01	.06	.17	.24	.20	.10	.02	0.00	.00
	.00	.02	.18	.89	2.01	2.55	2.01	.89	.18	.02	.00
56.00	.00	0.00	.03	.19	.51	.72	.62	.29	.06	.01	.00
	.00	.05	.55	2.68	6.09	7.72	6.09	2.68	.55	.05	.00
58.00	.00	0.00	.06	.39	1.02	1.44	1.24	.59	.13	.01	.00
	.00	.09	1.10	5.39	12.24	15.52	12.24	5.39	1.10	.09	.00
X(cm) =	.00	2.00	4.00	6.00	8.00	10.00	12.00	14.00	16.00	18.00	20.00

i @ z = 192.5 Y = 58.0

SEE FIG 1

i_0 @ x = 8.0 cm ; Y = 58.0 cm (EXAMPLE)

BEAM SHAPE AT ACCELERATOR EXIT

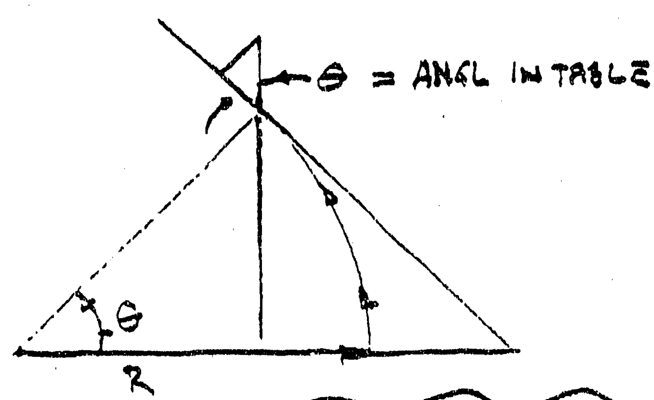


½ HALF ANGLE DIVERGENCE

X - DIRECTION = 0.0046 RAD

Y - DIRECTION = 0.0069 RAD

i = 0.88 AMPS @ ACCELERATOR EXIT / CHANNEL



BEAM DUMP DESIGN FOR NBETF @ 2 kW/cm² WAS CONTROLLED BY

3/28/96

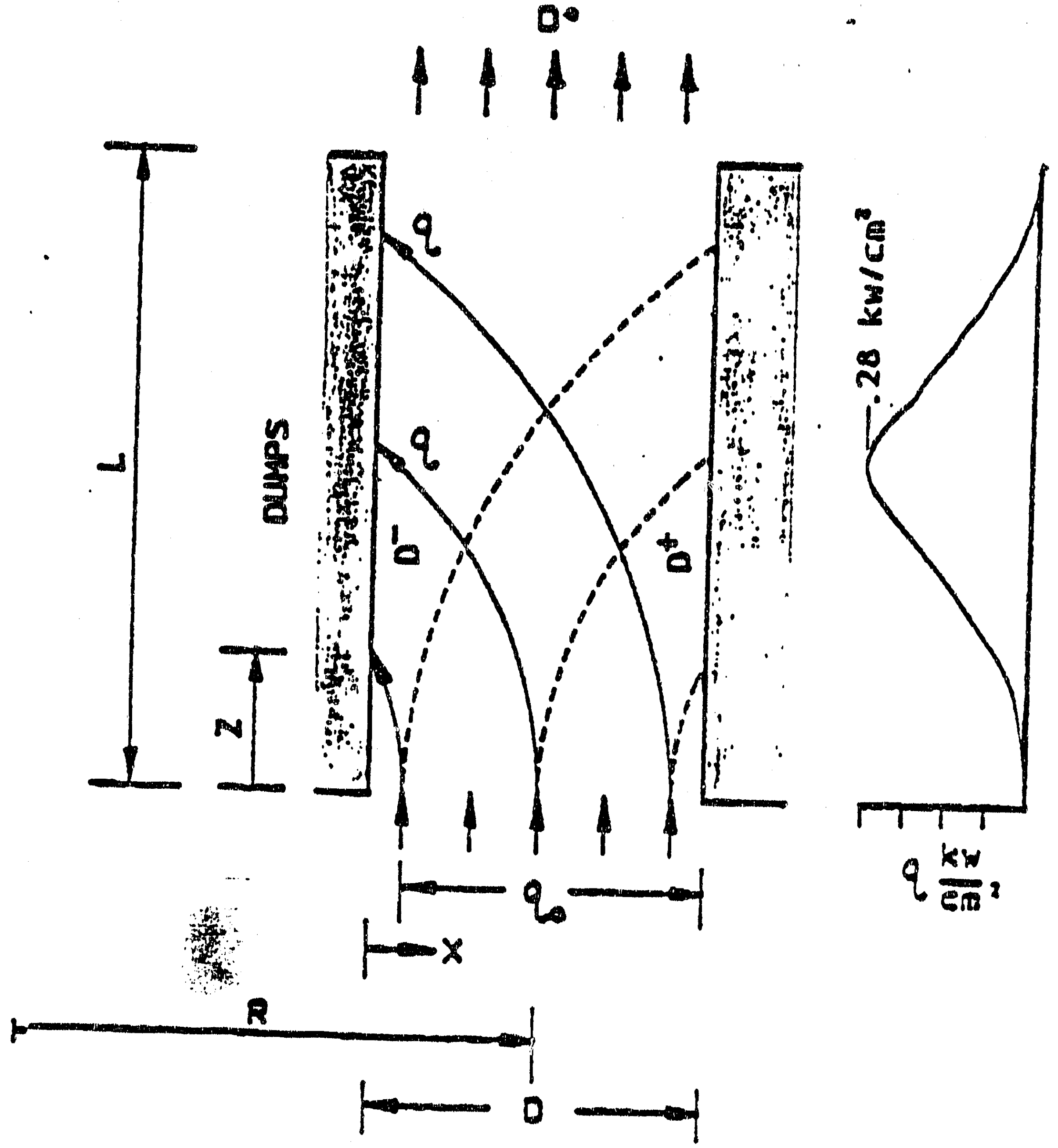
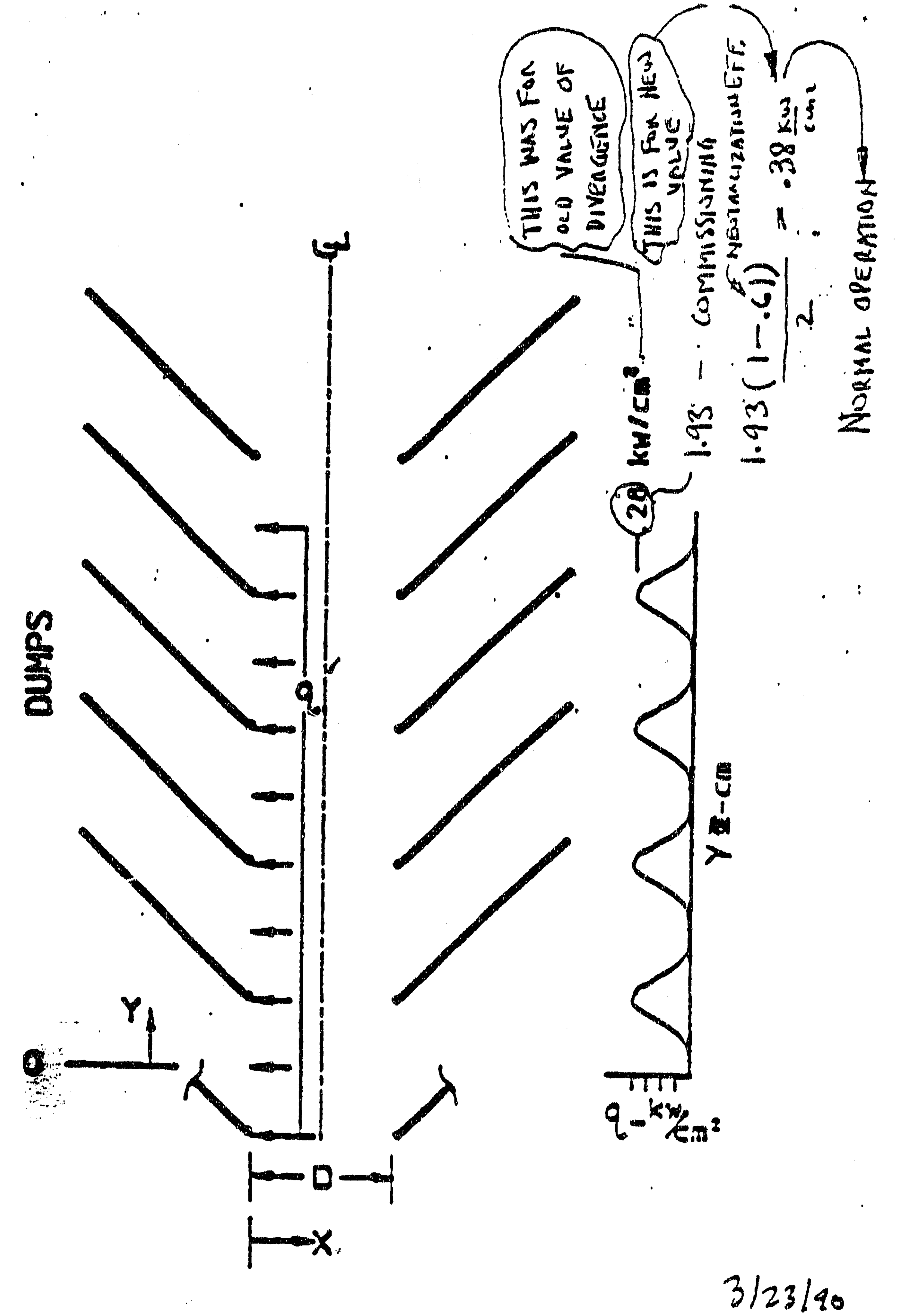


Fig 1 **ELECTROMAGNETIC DEFLECTOR AND BEAMDUMPS PLAN VIEW**



3/23/90

FIG 2. ELECTROMAGNETIC DEFLECTOR AND BEAMDUMPS
ELEVATION VIEW

Received 4/5/90

Lawrence Berkeley Laboratory
1 Cyclotron Road Berkeley, California 94720
(415) 486-4000 • FTS 451-4000

COVER SHEET

DATE: 4-5-90

TO: Doug Sedgley FAX No (516) 575-6619

Grumman Space Systems Verify (516) 575-8669

B29-25

Will call to discuss the cryo connections

FROM:

Peter Purcell

NUMBER OF PAGES 3 (PLUS COVER SHEET)

TELECOPIER INFORMATION:

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Verify Number: (415) 486-5011 – FTS 451-5011

Xerox 295 Unattended Automatic Machine (24 hours)

29 March 1990

To: V. Parail
W. Lindquist

From: C. Vallone
M. Sirone

Subject: NBI Information Needed to Develop Building Layout

Additional information (even preliminary) is needed in order to proceed with the development of the building layout for the NBI equipment.

This information is needed to clarify the maintenance procedures (module removal either sideways or backwards) and to clarify the location and space needed for the NBI auxiliary systems such as the cryopumps, the coolant water piping, and the power supplies.

Casual input suggests that many cryopumps will be needed surrounding each NBI module which will make the access very difficult. Therefore clarification is essential.

With reference to the attached sketch, the information needed is the following:

NBI Cryopumping System:

1. What is the number of cryopumps required, per module and total? What are the physical dimensions of each pump?

2. What is the number and dimensions of intermediate pumps?

3. Where are the pumps to be located?

4. What is the vacuum level required inside the module? Inside the NBI line?

Water Cooling System:

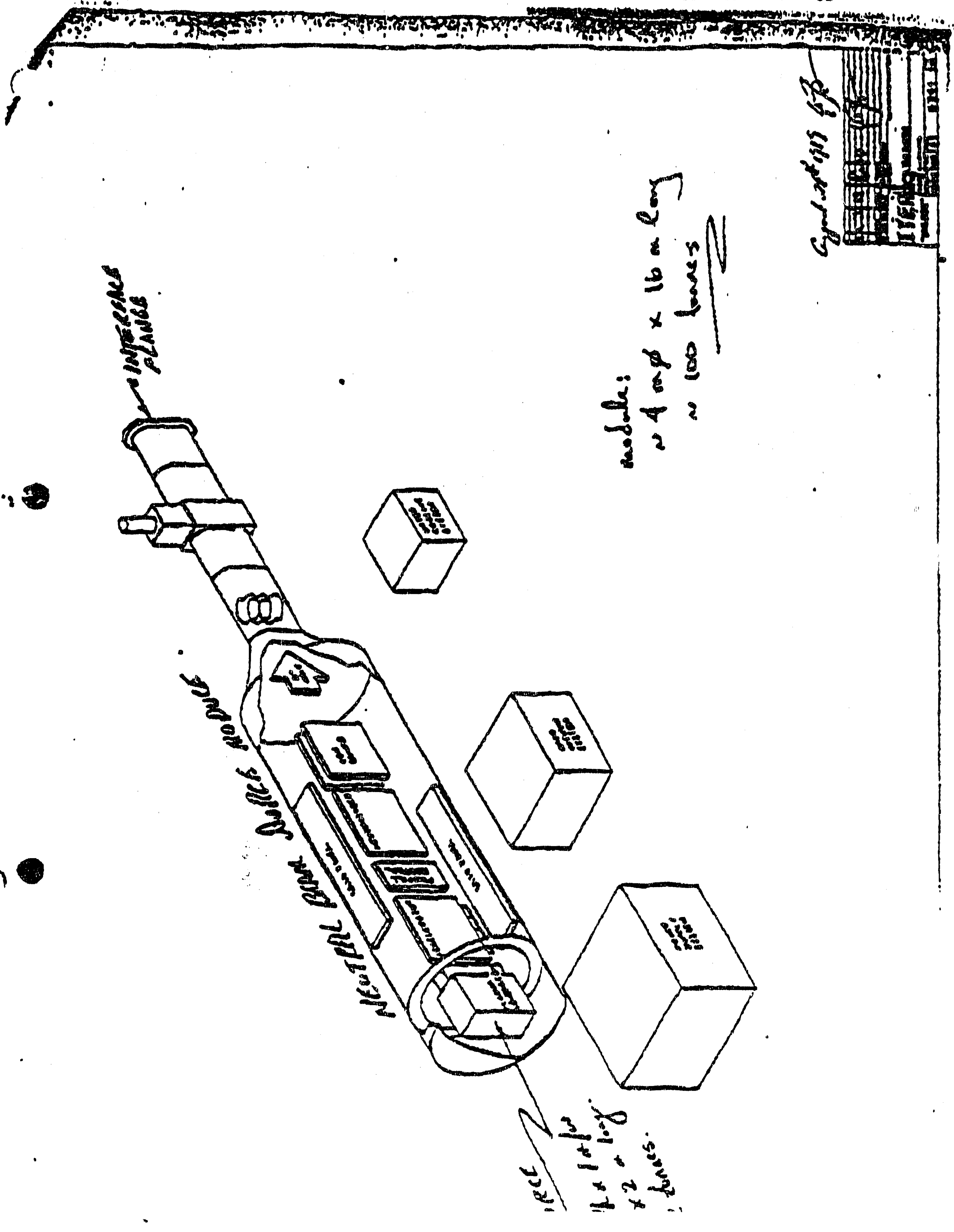
1. What is the number of pipes per module needed to provide the required cooling? What is the diameter of the pipes? What is the routing of the pipes relative to the attached sketch (or to other appropriate drawings for the NBI system)?

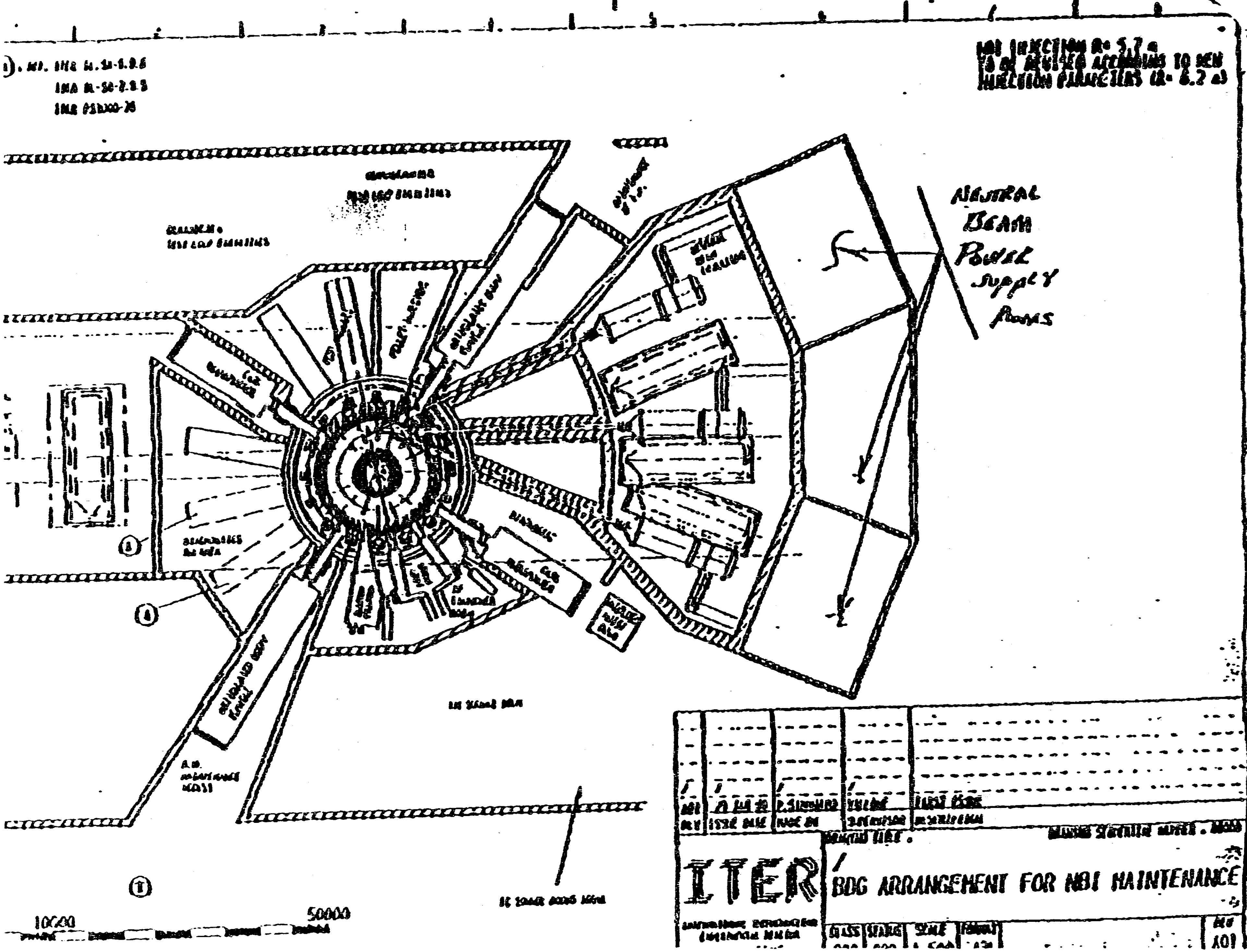
Power Supplies:

1. We assume that the power supplies will be located in adjacent room space and that the routing of the electrical leads will not compromise access to the NBI modules for maintenance; is this correct?. Are there any special considerations regarding the routing of the power supply bus lines to the NBI modules?

Please provide the requested information at your earliest convenience.

Please contact C. Vallone (49-89-329902-278) for additional clarification of the needed information, or to dicuss any aspects of


NEUTRAL BEAM INJECTOR MODULE
INTERFACE FLANGE
module:
~ 4 m ∅ x 16 m long
~ 100 tonnes


NBI INJECTION R= 5.7 m
TO BE REVISED ACCORDING TO NEW
INJECTION PARAMETERS (R= 6.2 m)
NEUTRAL
BEAM
POWER
SUPPLY
ROOMS
DIAGNOSTIC
BDG ARRANGEMENT FOR NBI MAINTENANCE
ITER
10000
50000

Lawrence Berkeley Laboratory
1 Cyclotron Road Berkeley, California 94720
(415) 486-4000 • FTS 451-4000

FACSIMILE COVER SHEET

DATE: May 8, 1990

TO: Doug Sedgley
Grumman

FAX #: (316) 575-6619

FROM: Peter Purgalis
Mail Stop 5/119

MESSAGE:

NUMBER OF PAGES 17 (PLUS COVER SHEET)

TELECOPIER INFORMATION:

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To: D. Sedgley May 8, 1990
From: P. Purgalis
Subject : Iter neutralize, dump and isolation valve apertures

Attached is following information:

Fig. 1	Beam power density profiles at plasma target	1 page
Fig. 2	Beamline components	1 page
Fig. 2a	Beamline components	1 page
Fig 3	Skim angle and beam envelope	1 page
Fig 4	Aiming parameters	1 page
File b1/cm	Uniform profile beam envelope	4 pages
File b3ax/cm	Peaked profile beam envelope	3 pages
File b2x/cm	Hollow profile beam envelope	3 pages

To get the uniform, peaked, and hollow power density profiles shown in Fig. 1 the beams have to be aimed at different positions at the plasma target. This is achieved by mechanically aiming the source/accelerator assemblies,during installation,to get a uniform power density profile. Each source is aimed as a unit so the four beams are parallel to each other. To get the peaked and hollow profiles electromagnets at the neutralizer entrance deflect the beams to reposition them on the target.The four beams from each source are deflected by one magnet.

File b1/cm shows the aiming parameters,for a uniform power density profile,for the center module of the neutral beam system. Shown in the tables are the coordinates of the beam centerlines at the accelerator exit; the beam centerlines and envelopes at the neutralizer entrance, the neutralizer exit, the dump exit, and the module isolation valve.

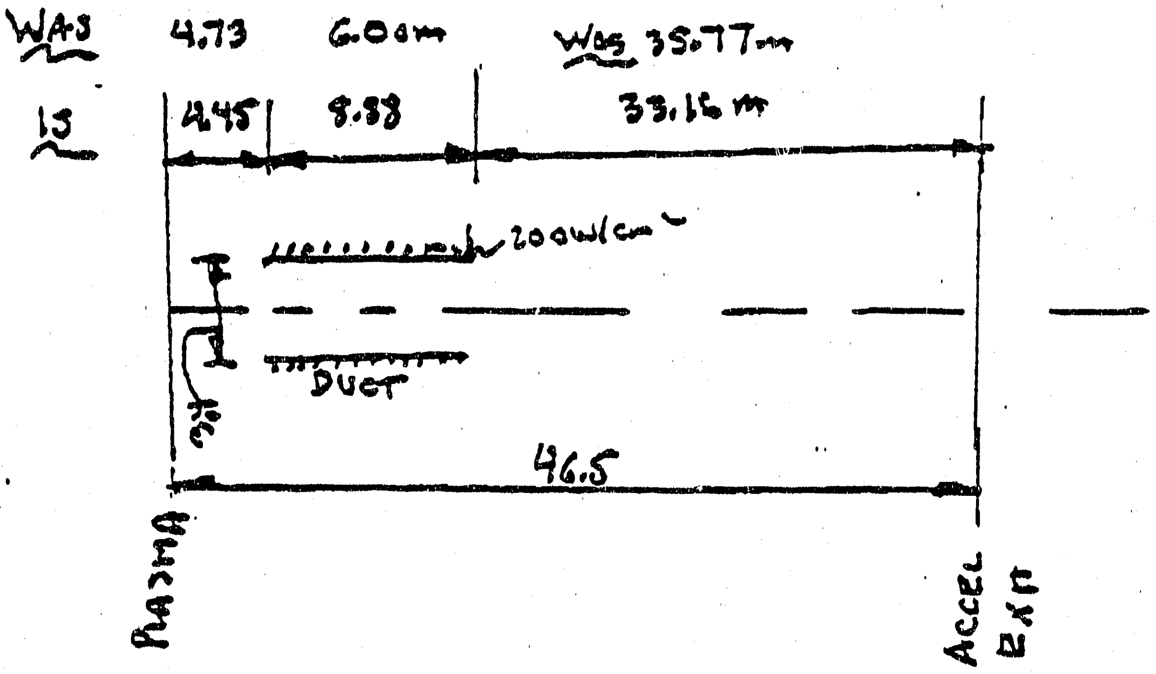
The same information is shown for the peaked and hollow power density profiles in files b3ax/cm and b2x/cm. For these two cases the beam path is identical to the uniform case up to the neutralizer entrance. As a result there are individual openings at the neutralizer entrance for each beam and the opening size and location is identical for the three profile cases. Down stream in the neutralizer the cross section of the beam passages increases and merge because of beam divergence and to accommodate the beam position for all three profile cases.

The enclosed information should be enough to size the neutralizer and to do the gas pumping analysis. The next work session in Garching is July 9-13. To include your work in the final report we need as much input as possible by the end of June. Only limited amount of additions can be made after that date.

Another item we need input on is reliability. Please send us a brief write up of what procedure would you follow in making a reliability analysis of the neutral beam system. What tools (computer codes) would you use and what information would you need?

cc W. Cooper w/attach
W. Lindquist w/attach

5/2/90
P. Duncan



Data from "Iter/prof/4/90" c

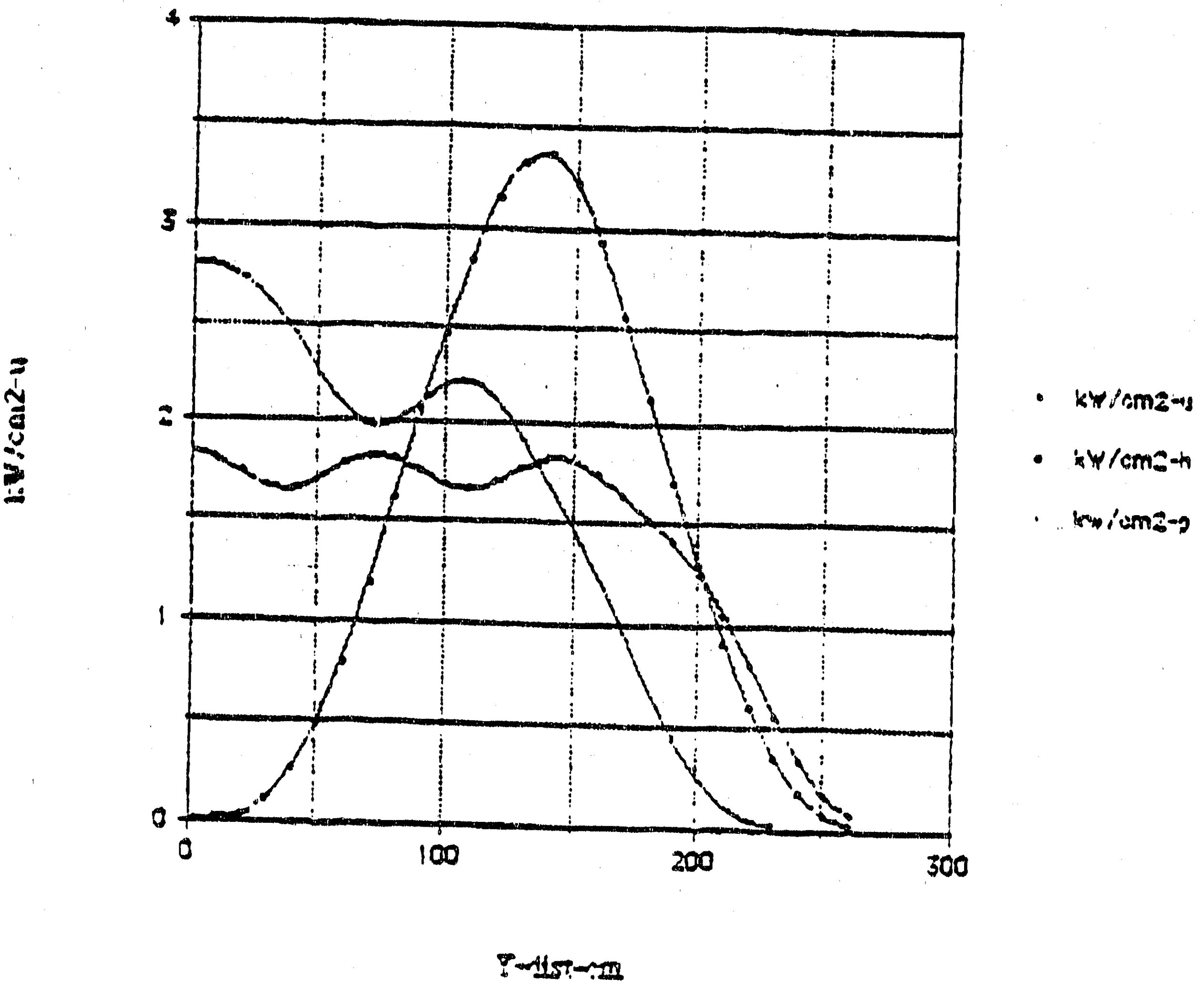
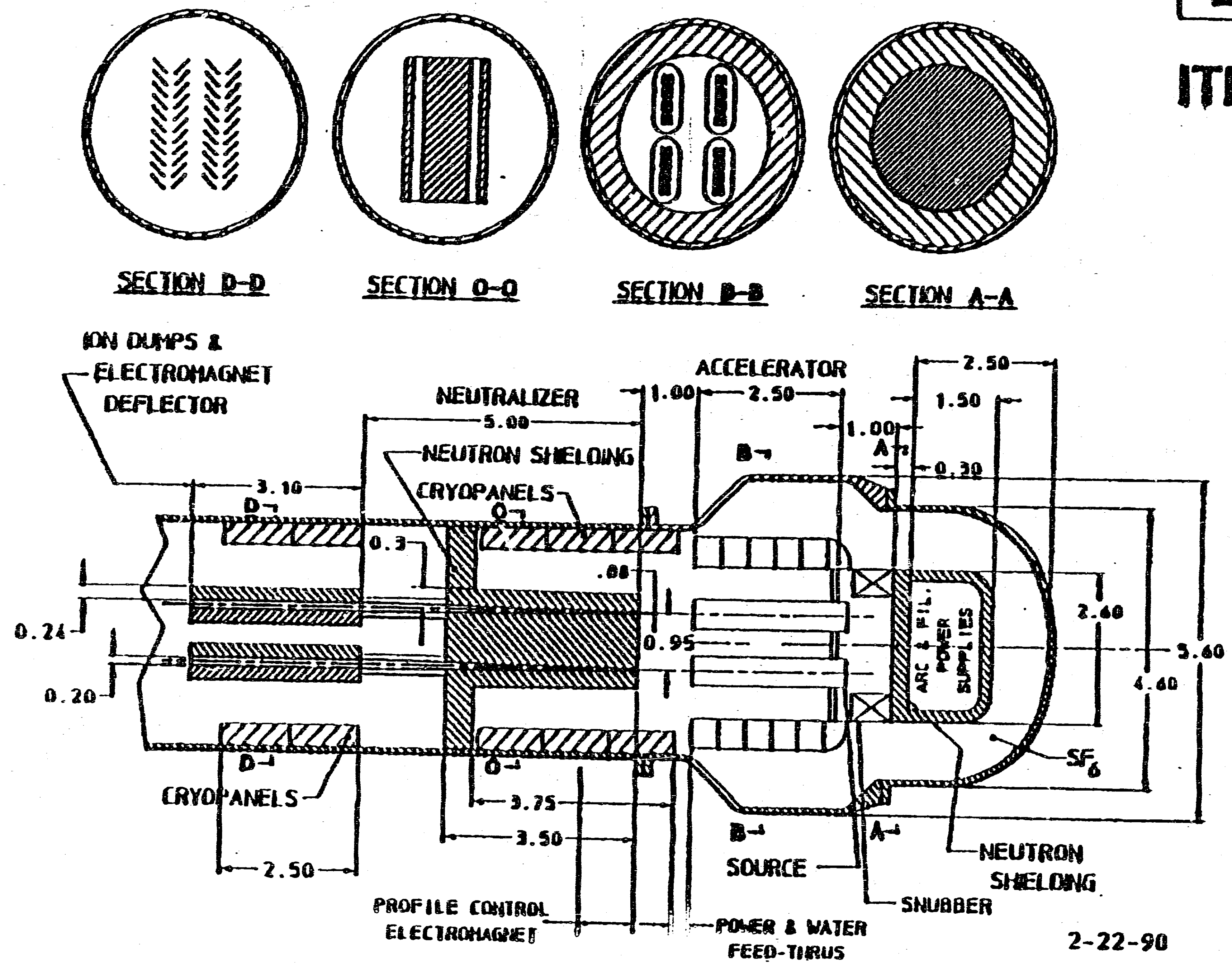


FIG 1 BEAM POWER DENSITY PROFILES
AT PLASMA

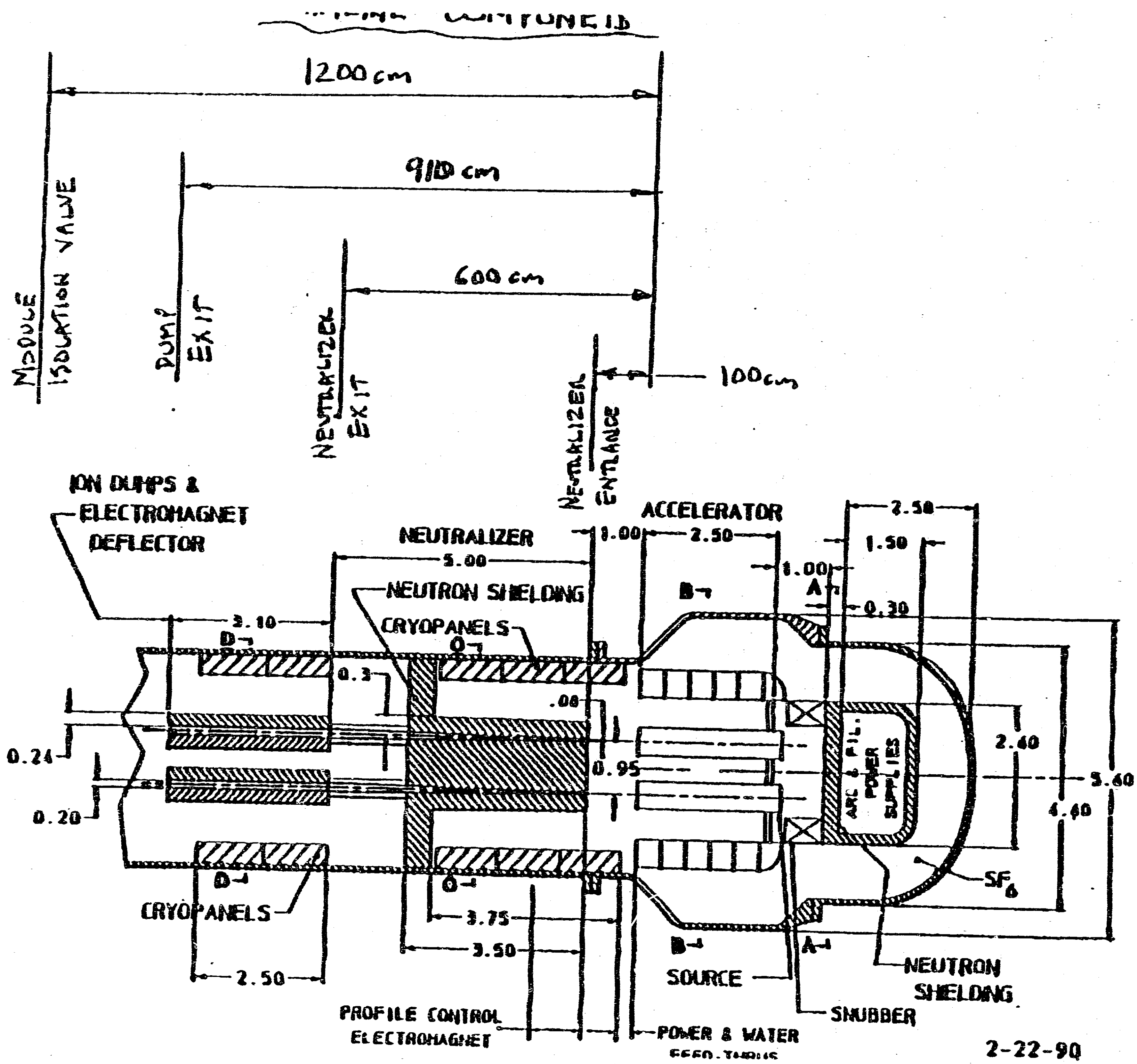
Fig 2

NEUTRAL BEAM CURRENT DRIVE SYSTEM – BEAM LINE COMPONENTS

ITER



2-22-90



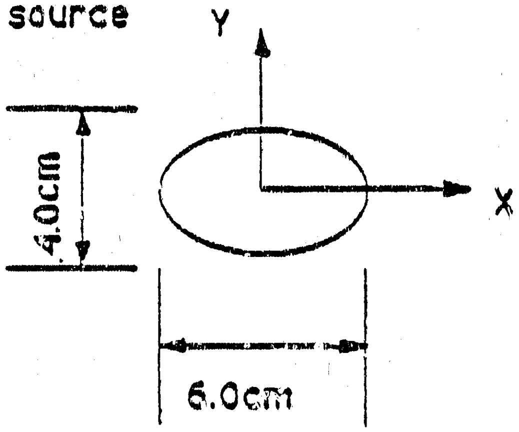
1200 cm
910 cm
600 cm
100 cm
MODULE ISOLATION VALVE
DUMP EXIT
NEUTRALIZER EXIT
NEUTRALIZER ENTRANCE
ION DUMPS & ELECTROMAGNET DEFLECTOR
NEUTRALIZER
ACCELERATOR
NEUTRON SHIELDING
CRYOPANELS
ARC & FIL. POWER SUPPLIES
SF6
SOURCE
SNUBBER
PROFILE CONTROL ELECTROMAGNET
POWER & WATER
2.50
1.50
1.00
0.30
2.40
5.60
4.40
0.95
.08
0.3
3.10
5.00
3.75
3.50
0.24
0.20
2-22-90

Fig 3

SKIM ANGLE AND BEAM ENVELOPE

P.Purgalis
5/7/90

From computer simulation:
Beamlet at Accelerator exit for a barium surface conversion source



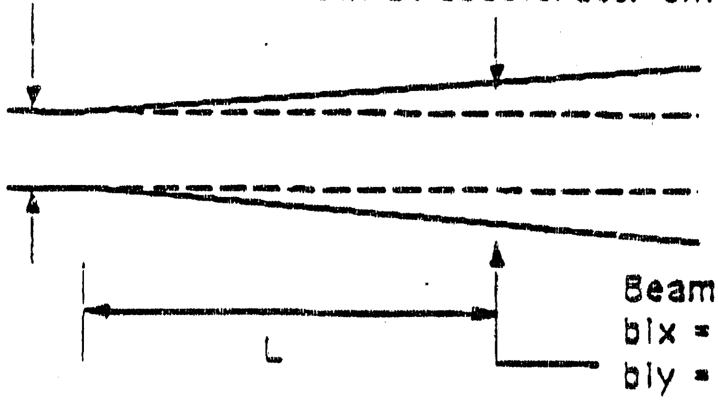
1/e half angle divergence
$wxe = 0.0046$ rad
$wye = 0.0069$ rad

For beamline design increase divergence by 50% and add 0.001 radian for misalignment. The resulting skim half angles are :

$wxs = 0.0046 \times 1.5 + 0.001 = 0.0079$ radians
$wys = 0.0069 \times 1.5 + 0.001 = 0.0114$ radians
These skim angles correspond to approximately 98 % transmission

Using these half angles the envelope of the individual beamlets is:

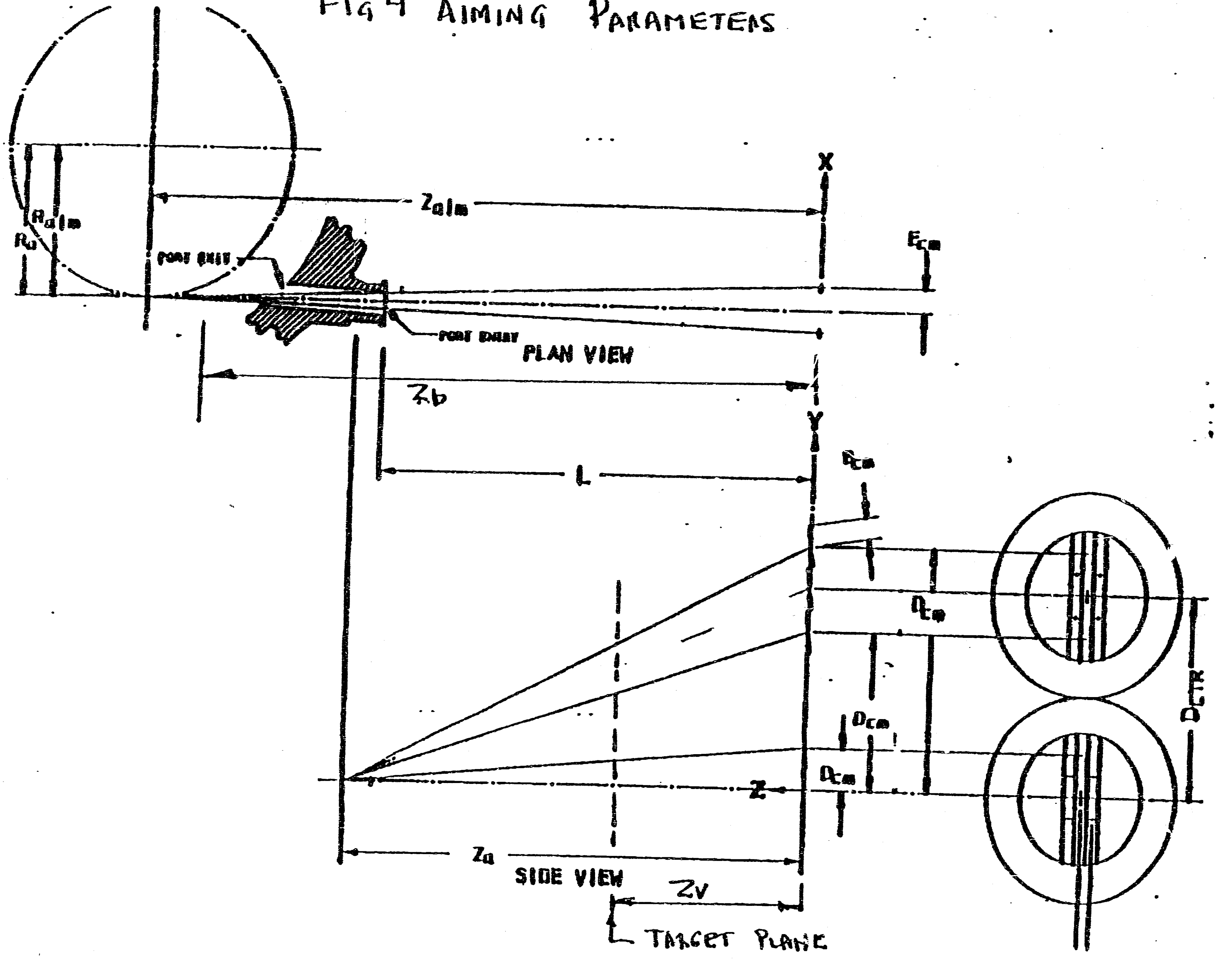
Beamlet width at accelerator exit bx & by



Beamlet width at distance L
$blx = bx + 2 \times wxs \times L$
$bly = by + 2 \times wys \times L$

Location	L-cm	blx-cm	bly-cm
Accelerator exit	0.0	6.0	4.0
Neutralizer entrance	100.0	8.0	7.0
Neutralizer exit/ Dump entrance	600.0	15.5	18.0
Dump exit	910.0	20.5	25.0
Module isolation valve	1200.0	25.0	31.5

Fig 4 Aiming Parameters



beamc

FILE: b1/cm UNIFORM PROFILE BEAM ENVELOPE

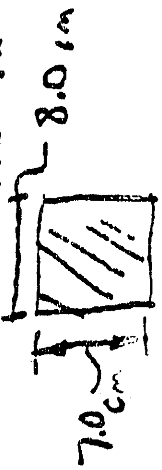
b1/cm
1/4

title: iter 1.3mev/1A/4 bmlts/sorce 10MW/mod $\boxed{\text{uniform, one module,}}$ 5/07/90

file: iter/b1/cm

Beam cluster centerline tangent radius Ro	=	6.200 m
Beam energy	=	1.300 MeV
Beam power per channel delivered	=	.640 MW
Total beam power delivered	=	10.240 MW for 16 channels
Beamlet width at accelerator exit	=	6.000 cm

For NEUTRALIZER ENTRANCE USE ROUNDED UP VALUES FOR BEAM ENVELOPE

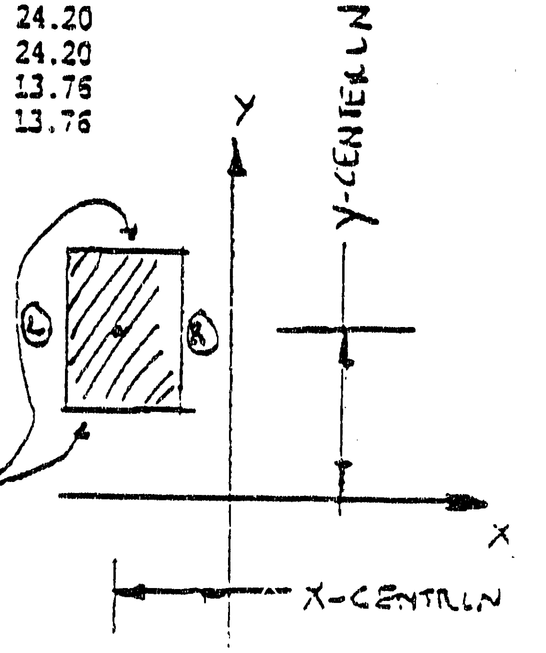


SEGMENT SIZE AND LOCATION (Accelerator exit)

Segment No	Height 2*Bcm cm	Dist to segmnt Center x-dir Ecm cm	y-dir Dcm cm	Aiming Radius Raim m	Dist-h Zaim m	Dist-v Za m
1	4.00	47.50	29.01	6.20	41.77	13.76
2	4.00	-47.50	29.01	6.20	41.77	13.76
3	4.00	47.50	51.00	6.20	41.77	24.20
4	4.00	-47.50	51.00	6.20	41.77	24.20
5	4.00	47.50	73.00	6.20	41.77	34.64
6	4.00	-47.50	73.00	6.20	41.77	34.64
7	4.00	47.50	94.99	6.20	41.77	45.07
8	4.00	-47.50	94.99	6.20	41.77	45.07
9	4.00	-47.50	-94.99	6.20	41.77	45.07
10	4.00	47.50	-94.99	6.20	41.77	45.07
11	4.00	-47.50	-73.00	6.20	41.77	34.64
12	4.00	47.50	-73.00	6.20	41.77	34.64
13	4.00	-47.50	-51.00	6.20	41.77	24.20
14	4.00	47.50	-51.00	6.20	41.77	24.20
15	4.00	-47.50	-29.01	6.20	41.77	13.76
16	4.00	47.50	-29.01	6.20	41.77	13.76

Skim half angles x-dir = .0079 rad y-dir = .0114 rad

At target plane distance (Zv) = 1.00 m(from accelerator exit)
Target plane is neutralizer entance
Beam envelope for the given skim angles



Seg no	Horiz xovr distance Zb-m	x-centrln cm	x-env l/r (LEFT, RIGHT) cm	y-centrln cm	y-env t/b (TOP, BOTTOM) cm
1	41.770	-46.363	-42.573 (L)	26.902	30.042
			-50.153 (R)		23.762
2	41.770	46.363	50.153	26.902	30.041
			42.573		23.762
3	41.770	-46.363	-42.573	48.893	52.032
			-50.153		45.753
4	41.770	46.363	50.153	48.893	52.032
			42.573		45.753
5	41.770	-46.363	-42.573	70.393	74.032

bi/cm
2/24

			-50.153		67.753
6	41.770	46.363	50.153 42.573	70.893	74.032 67.753
7	41.770	-46.363	-42.573 -50.153	92.882	96.022 89.743
8	41.770	46.363	50.153 42.573	92.882	96.022 89.743
9	41.770	46.363	50.153 42.573	-92.882	-89.743 -96.022
10	41.770	-46.363	-42.573 -50.153	-92.882	-89.743 -96.022
11	41.770	46.363	50.153 42.573	-70.893	-67.753 -74.032
12	41.770	-46.363	-42.573 -50.153	-70.893	-67.753 -74.032
13	41.770	46.363	50.153 42.573	-48.893	-45.753 -52.032
14	41.770	-46.363	-42.573 -50.153	-48.893	-45.753 -52.032
15	41.770	46.363	50.153 42.573	-26.902	-23.762 -30.041
16	41.770	-46.363	-42.573 -50.153	-26.902	-23.762 -30.041

At target plane distance (Zv) = 6.00 m(from accelerator exit)
Target plane is neutralizer exit
Beam envelope for the given skim angles

Seg no	Horiz xovr distance Zb-m	x-centrln cm	x-env l/r cm	y-centrln cm	y-env t/b cm
1	41.770	-40.677	-32.937 -48.417	16.360	25.200 7.521
2	41.770	40.677	48.417 32.937	16.360	25.200 7.521
3	41.770	-40.677	-32.937 -48.417	38.355	47.195 29.516
4	41.770	40.677	48.417 32.937	38.355	47.195 29.516
5	41.770	-40.677	-32.937 -48.417	60.356	69.195 51.516
6	41.770	40.677	48.417 32.937	60.356	69.195 51.516
7	41.770	-40.677	-32.937 -48.417	82.344	91.184 73.505
8	41.770	40.677	48.417 32.937	82.344	91.184 73.505
9	41.770	40.677	48.417 32.937	-82.344	-73.505 -91.184
10	41.770	-40.677	-32.937 -48.417	-82.344	-73.505 -91.184
11	41.770	40.677	48.417 32.937	-60.356	-51.516 -69.195
12	41.770	-40.677	-32.937 -48.417	-60.356	-51.516 -69.195
13	41.770	40.677	48.417	-38.355	-29.516

b1/cm
3/4

			32.937		-47.195
14	41.770	-40.677	-32.937	-38.355	-29.516
			-48.417		-47.195
15	41.770	40.677	48.417	-16.360	-7.521
			32.937		-25.200
16	41.770	-40.677	-32.937	-16.360	-7.521
			-48.417		-25.200

At target plane distance (Zv) = 9.10 m(from accelerator exit)
Targey plane is dump exit
Beam envelope for the given skim angles

Seg no	Horiz xovr distance Zb-m	x-centrln cm	x-env l/r cm	y-centrln cm	y-env t/b cm
1	41.770	-37.152	-26.963	9.825	22.198
			-47.340		-2.549
2	41.770	37.152	47.340	9.825	22.198
			26.963		-2.549
3	41.770	-37.152	-26.963	31.822	44.196
			-47.340		19.449
4	41.770	37.152	47.340	31.822	44.196
			26.963		19.449
5	41.770	-37.152	-26.963	53.823	66.196
			-47.340		41.449
6	41.770	37.152	47.340	53.823	66.196
			26.963		41.449
7	41.770	-37.152	-26.963	75.811	88.184
			-47.340		63.437
8	41.770	37.152	47.340	75.811	88.184
			26.963		63.437
9	41.770	37.152	47.340	-75.811	-63.437
			26.963		-88.184
10	41.770	-37.152	-26.963	-75.811	-63.437
			-47.340		-88.184
11	41.770	37.152	47.340	-53.823	-41.449
			26.963		-66.196
12	41.770	-37.152	-26.963	-53.823	-41.449
			-47.340		-66.196
13	41.770	37.152	47.340	-31.822	-19.449
			26.963		-44.196
14	41.770	-37.152	-26.963	-31.822	-19.449
			-47.340		-44.196
15	41.770	37.152	47.340	-9.825	2.549
			26.963		-22.198
16	41.770	-37.152	-26.963	-9.825	2.549
			-47.340		-22.198

At target plane distance (Zv) = 12.00 m(from accelerator exit)
Target plane is module isolation valve
Beam envelope for the given skim angles

Seg no	Horiz xovr distance Zb-m	x-centrln cm	x-env l/r cm	y-centrln cm	y-env t/b cm

61/cm
4/4

1	41.770	-33.854	-21.374 -46.334	3.711	19.390 -11.969
2	41.770	33.854	46.334 21.374	3.711	19.390 -11.969
3	41.770	-33.854	-21.374 -46.334	25.711	41.390 10.031
4	41.770	33.854	46.334 21.374	25.711	41.390 10.031
5	41.770	-33.854	-21.374 -46.334	47.711	63.391 32.032
6	41.770	33.854	46.334 21.374	47.711	63.391 32.032
7	41.770	-33.854	-21.374 -46.334	69.699	85.378 54.019
8	41.770	33.854	46.334 21.374	69.699	85.378 54.019
9	41.770	33.854	46.334 21.374	-69.699	-54.019 -85.378
10	41.770	-33.854	-21.374 -46.334	-69.699	-54.019 -85.378
11	41.770	33.854	46.334 21.374	-47.711	-32.032 -63.391
12	41.770	-33.854	-21.374 -46.334	-47.711	-32.032 -63.391
13	41.770	33.854	46.334 21.374	-25.711	-10.031 -41.390
14	41.770	-33.854	-21.374 -46.334	-25.711	-10.031 -41.390
15	41.770	33.854	46.334 21.374	-3.711	11.969 -19.390
16	41.770	-33.854	-21.374 -46.334	-3.711	11.969 -19.390

beamc FILE: b3ax/cm PEAKED PROFILE BEAM ENVELOPE

b3ax/cm

1/3

title: iter 1.3mev/1A/4 bmlts/segment 10MW/mod $\boxed{\text{peaked, one module}}$ 5/04/90

file: iter/b3ax/cm

Beam cluster centerline tangent radius	Ro =	6.200 m	
Beam energy	=	1.300 MeV	
Beam power per channel delivered	=	.640 MW	
Total beam power delivered	=	10.240 MW for	16 channels
Beamlet width at accelerator exit	=	6.000 cm	

SEGMENT SIZE AND LOCATION (Accelerator exit)

Segment No	Height 2*Bcm cm	Dist to segmnt Center x-dir Bcm cm	y-dir Dcm cm	Aiming Radius Raim m	Dist-h Zaim m	Dist-v Za m
1	4.00	47.50	26.90	6.20	41.77	20.44
2	4.00	-47.50	26.90	6.20	41.77	20.44
3	4.00	47.50	48.90	6.20	41.77	37.15
4	4.00	-47.50	48.90	6.20	41.77	37.15
5	4.00	47.50	70.90	6.20	41.77	53.85
6	4.00	-47.50	70.90	6.20	41.77	53.85
7	4.00	47.50	92.90	6.20	41.77	70.56
8	4.00	-47.50	92.90	6.20	41.77	70.56
9	4.00	-47.50	-92.90	6.20	41.77	70.56
10	4.00	47.50	-92.90	6.20	41.77	70.56
11	4.00	-47.50	-70.90	6.20	41.77	53.85
12	4.00	47.50	-70.90	6.20	41.77	53.85
13	4.00	-47.50	-48.90	6.20	41.77	37.15
14	4.00	47.50	-48.90	6.20	41.77	37.15
15	4.00	-47.50	-26.90	6.20	41.77	20.44
16	4.00	47.50	-26.90	6.20	41.77	20.44

Skim half angles x-dir = .0079 rad y-dir = .0114 rad

At target plane distance (Zv) = 5.00 m(from neutralizer entrance)

Target plane is neutralizer exit

Beam envelope for the given skim angles

Seg no	Horiz xovr distance Zb-m	x-centrln cm	x-env l/r cm	y-centrln cm	y-env t/b cm
1	41.770	-41.814	-34.864	20.320	28.020
			-48.764		12.620
2	41.770	41.814	48.764	20.320	28.020
			34.864		12.620
3	41.770	-41.814	-34.864	42.319	50.018
			-48.764		34.619
4	41.770	41.814	48.764	42.319	50.018
			34.864		34.619
5	41.770	-41.814	-34.864	64.317	72.017

			-48.764		56.617
6	41.770	41.814	48.764	64.317	72.017
			34.864		56.617
7	41.770	-41.814	-34.864	86.317	94.017
			-48.764		78.617
8	41.770	41.814	48.764	86.317	94.017
			34.864		78.617
9	41.770	41.814	48.764	-86.317	-78.617
			34.864		-94.017
10	41.770	-41.814	-34.864	-86.317	-78.617
			-48.764		-94.017
11	41.770	41.814	48.764	-64.317	-56.617
			34.864		-72.017
12	41.770	-41.814	-34.864	-64.317	-56.617
			-48.764		-72.017
13	41.770	41.814	48.764	-42.319	-34.619
			34.864		-50.018
14	41.770	-41.814	-34.864	-42.319	-34.619
			-48.764		-50.018
15	41.770	41.814	48.764	-20.320	-12.620
			34.864		-28.020
16	41.770	-41.814	-34.864	-20.320	-12.620
			-48.764		-28.020

b3ax/cm
2/3

At target plane distance (Zv) = 8.10 m(from neutralizer entrance)
Target plane is dump exit
Beam envelope for the given skim angles

Seg no	Horiz xovr distance Zb-m	x-centrln cm	x-env l/r cm	y-centrln cm	y-env t/b cm
1	41.770	-38.289	-28.890	16.240	27.474
			-47.688		5.006
2	41.770	38.289	47.688	16.240	27.474
			28.890		5.006
3	41.770	-38.289	-28.890	38.238	49.472
			-47.688		27.004
4	41.770	38.289	47.688	38.238	49.472
			28.890		27.004
5	41.770	-38.289	-28.890	60.235	71.469
			-47.688		49.002
6	41.770	38.289	47.688	60.235	71.469
			28.890		49.002
7	41.770	-38.289	-28.890	82.235	93.469
			-47.688		71.002
8	41.770	38.289	47.688	82.235	93.469
			28.890		71.002
9	41.770	38.289	47.688	-82.235	-71.002
			28.890		-93.469
10	41.770	-38.289	-28.890	-82.235	-71.002
			-47.688		-93.469
11	41.770	38.289	47.688	-60.235	-49.002
			28.890		-71.469
12	41.770	-38.289	-28.890	-60.235	-49.002
			-47.688		-71.469
13	41.770	38.289	47.688	-38.238	-27.004

b3ax/cm

3/3

			28.890		-49.472
14	41.770	-38.289	-28.890	-38.238	-27.004
			-47.688		-49.472
15	41.770	38.289	47.688	-16.240	-5.006
			28.890		-27.474
16	41.770	-38.289	-28.890	-16.240	-5.006
			-47.688		-27.474

At target plane distance (Zv) = 11.00 m(from neutralizer entrance)
Target plane is module isolation valve
Beam envelope for the given skim angles

Seg no	Horiz xovr distance Zb-m	x-centrln cm	x-env l/r cm	y-centrln cm	y-env t/b cm
1	41.770	-34.991	-23.301	12.423	26.963
			-46.681		-2.116
2	41.770	34.991	46.681	12.423	26.963
			23.301		-2.116
3	41.770	-34.991	-23.301	34.421	48.961
			-46.681		19.881
4	41.770	34.991	46.681	34.421	48.961
			23.301		19.881
5	41.770	-34.991	-23.301	56.417	70.957
			-46.681		41.877
6	41.770	34.991	46.681	56.417	70.957
			23.301		41.877
7	41.770	-34.991	-23.301	78.417	92.957
			-46.681		63.877
8	41.770	34.991	46.681	78.417	92.957
			23.301		63.877
9	41.770	34.991	46.681	-78.417	-63.877
			23.301		-92.957
10	41.770	-34.991	-23.301	-78.417	-63.877
			-46.681		-92.957
11	41.770	34.991	46.681	-56.417	-41.877
			23.301		-70.957
12	41.770	-34.991	-23.301	-56.417	-41.877
			-46.681		-70.957
13	41.770	34.991	46.681	-34.421	-19.881
			23.301		-48.961
14	41.770	-34.991	-23.301	-34.421	-19.881
			-46.681		-48.961
15	41.770	34.991	46.681	-12.423	2.116
			23.301		-26.963
16	41.770	-34.991	-23.301	-12.423	2.116
			-46.681		-26.963

beamc

b2x/cm
1/3

FILE: b2x/cm HOLLOW PROFILE BEAM ENVELOPE

title: iter 1.3mev/1A/4 bmlts/source 10MW/mod $\boxed{\text{hollow,one module}}$ 5/04/90

file: iter/b2x/cm

Beam cluster centerline tangent radius Ro	=	6.200 m	
Beam energy	=	1.300 MeV	
Beam power per channel delivered	=	.640 MW	
Total beam power delivered	=	10.240 MW for	16 channels
Beamlet width at accelerator exit	=	6.000 cm	

SEGMENT SIZE AND LOCATION (Accelerator exit)

Segment No	Height 2*Bcm cm	Dist to segmnt Center x-dir Scm cm	y-dir Dcm cm	Aiming Radius Raim m	Dist-h Zaim m	Dist-v Za m
1	4.00	47.50	26.92	6.20	41.77	7.43
2	4.00	-47.50	26.92	6.20	41.77	7.43
3	4.00	47.50	48.91	6.20	41.77	13.49
4	4.00	-47.50	48.91	6.20	41.77	13.49
5	4.00	47.50	70.89	6.20	41.77	19.56
6	4.00	-47.50	70.89	6.20	41.77	19.56
7	4.00	47.50	92.88	6.20	41.77	25.63
8	4.00	-47.50	92.88	6.20	41.77	25.63
9	4.00	-47.50	-92.88	6.20	41.77	25.63
10	4.00	47.50	-92.88	6.20	41.77	25.63
11	4.00	-47.50	-70.89	6.20	41.77	19.56
12	4.00	47.50	-70.89	6.20	41.77	19.56
13	4.00	-47.50	-48.91	6.20	41.77	13.49
14	4.00	47.50	-48.91	6.20	41.77	13.49
15	4.00	-47.50	-26.92	6.20	41.77	7.43
16	4.00	47.50	-26.92	6.20	41.77	7.43

Skim half angles x-dir = .0079 rad y-dir = .0114 rad

At target plane distance (Zv) = 5.00 m(from neutralizer entrance)
Target plane is neutralizer exit
Beam envelope for the given skim angles

Seg no	Horiz xovr distance Zb-w	x-centrln cm	x-env l/r cm	y-centrln cm	y-env t/b cm
1	41.770	-41.814	-34.864	8.804	16.503
			-48.764		1.106
2	41.770	41.814	48.764	8.804	16.503
			34.864		1.106
3	41.770	-41.814	-34.864	30.782	38.480
			-48.764		23.083
4	41.770	41.814	48.764	30.782	38.480
			34.864		23.083
5	41.770	-41.814	-34.864	52.769	60.468

b 2x/cm
2/3

			-48.764		45.070
6	41.770	41.814	48.764	52.769	60.468
			34.864		45.070
7	41.770	-41.814	-34.864	74.761	82.459
			-48.764		67.062
8	41.770	41.814	48.764	74.761	82.459
			34.864		67.062
9	41.770	41.814	48.764	-74.761	-67.062
			34.864		-82.459
10	41.770	-41.814	-34.864	-74.761	-67.062
			-48.764		-82.459
11	41.770	41.814	48.764	-52.769	-45.070
			34.864		-60.468
12	41.770	-41.814	-34.864	-52.769	-45.070
			-48.764		-60.468
13	41.770	41.814	48.764	-30.782	-23.083
			34.864		-38.480
14	41.770	-41.814	-34.864	-30.782	-23.083
			-48.764		-38.480
15	41.770	41.814	48.764	-8.804	-1.106
			34.864		-16.503
16	41.770	-41.814	-34.864	-8.804	-1.106
			-48.764		-16.503

At target plane distance (Zv) = 8.10 m(from neutralizer entrance)
Target plane is dump exit
Beam envelope for the given skim angles

Seg no	Horiz xovr distance Zb-m	x-centrln cm	x-env l/r cm	y-centrln cm	y-env t/b cm
1	41.770	-38.289	-28.890	-2.428	8.805
			-47.688		-13.660
2	41.770	38.289	47.688	-2.428	8.805
			28.890		-13.660
3	41.770	-38.289	-28.890	19.542	30.775
			-47.688		8.310
4	41.770	38.289	47.688	19.542	30.775
			28.890		8.310
5	41.770	-38.289	-28.890	41.534	52.766
			-47.688		30.301
6	41.770	38.289	47.688	41.534	52.766
			28.890		30.301
7	41.770	-38.289	-28.890	63.527	74.759
			-47.688		52.294
8	41.770	38.289	47.688	63.527	74.759
			28.890		52.294
9	41.770	38.289	47.688	-63.527	-52.294
			28.890		-74.759
10	41.770	-38.289	-28.890	-63.527	-52.294
			-47.688		-74.759
11	41.770	38.289	47.688	-41.534	-30.301
			28.890		-52.766
12	41.770	-38.289	-28.890	-41.534	-30.301
			-47.688		-52.766
13	41.770	38.289	47.688	-19.542	-8.310

bzx/cm
3/3

			28.890		-30.775
14	41.770	-38.289	-28.890 -47.688	-19.542	-8.310 -30.775
15	41.770	38.289	47.688 28.890	2.428	13.660 -8.805
16	41.770	-38.289	-28.890 -47.688	2.428	13.660 -8.805

At target plane distance (Zv) = 11.00 m(from neutralizer entrance)
Target plane is module isolation valve
Beam envelope for the given skim angles

Seg no	Horiz xovr distance Zb-m	x-centrln cm	x-env l/r cm	y-centrln cm	y-env t/b cm
1	41.770	-34.991	-23.301 -46.681	-12.935	1.604 -27.473
2	41.770	34.991	46.681 23.301	-12.935	1.604 -27.473
3	41.770	-34.991	-23.301 -46.681	9.028	23.567 -5.511
4	41.770	34.991	46.681 23.301	9.028	23.567 -5.511
5	41.770	-34.991	-23.301 -46.681	31.023	45.562 16.485
6	41.770	34.991	46.681 23.301	31.023	45.562 16.485
7	41.770	-34.991	-23.301 -46.681	53.017	67.556 38.479
8	41.770	34.991	46.681 23.301	53.017	67.556 38.479
9	41.770	34.991	46.681 23.301	-53.017	-38.479 -67.556
10	41.770	-34.991	-23.301 -46.681	-53.017	-38.479 -67.556
11	41.770	34.991	46.681 23.301	-31.023	-16.485 -45.562
12	41.770	-34.991	-23.301 -46.681	-31.023	-16.485 -45.562
13	41.770	34.991	46.681 23.301	-9.028	5.511 -23.567
14	41.770	-34.991	-23.301 -46.681	-9.028	5.511 -23.567
15	41.770	34.991	46.681 23.301	12.935	27.473 -1.604
16	41.770	-34.991	-23.301 -46.681	12.935	27.473 -1.604

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Grumman

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beamc

FILE b2y/cm Hollow PROFILE
BEAM ENVELOPE

b2y/cm
1/3

ile: iter 1.3mev/1A/4 belts/source 10MW/mod hollow, one module 5/09/90

file: iter/b2y/cm

Beam cluster centerline tangent radius Ro	=	6.200 m
Beam energy	=	1.300 MeV
Beam power per channel delivered	=	.640 MW
Total beam power delivered	=	10.240 MW for 16 channels
Beamlet width at accelerator exit	=	7.580 cm

SEGMENT SIZE AND LOCATION (Accelerator exit)

Segment No	Height 2*Bcm cm	Dist to segmnt Center x-dir Ecm cm	y-dir Dcm cm	Aiming Radius Raim m	Dist-h Zaim m	Dist-v Za m
1	6.28	46.36	26.92	6.20	40.77	7.43
2	6.28	-46.36	26.92	6.20	40.77	7.43
3	6.28	46.36	48.91	6.20	40.77	13.49
4	6.28	-46.36	48.91	6.20	40.77	13.49
5	6.28	46.36	70.89	6.20	40.77	19.56
6	6.28	-46.36	70.89	6.20	40.77	19.56
7	6.28	46.36	92.88	6.20	40.77	25.63
8	6.28	-46.36	92.88	6.20	40.77	25.63
9	6.28	-46.36	-92.88	6.20	40.77	25.63
10	6.28	46.36	-92.88	6.20	40.77	25.63
11	6.28	-46.36	-70.89	6.20	40.77	19.56
12	6.28	46.36	-70.89	6.20	40.77	19.56
13	6.28	-46.36	-48.91	6.20	40.77	13.49
14	6.28	46.36	-48.91	6.20	40.77	13.49
15	6.28	-46.36	-26.92	6.20	40.77	7.43
16	6.28	46.36	-26.92	6.20	40.77	7.43

Skim half angles x-dir = .0079 rad y-dir = .0114 rad

At target plane distance (Zv) = 5.00 m(from neutralizer entrance)
Target plane is neutralizer exit
Beam envelope for the given skim angles

Seg no	Horiz xovr distance Zb-m	x-centrln cm	x-env l/r cm	y-centrln cm	y-env t/b cm
1	40.770	-40.674	-32.935	8.304	17.642
			-48.414		-.034
2	40.770	40.674	48.414	8.304	17.642
			32.935		-.034
3	40.770	-40.674	-32.935	30.782	39.620
			-48.414		21.944
4	40.770	40.674	48.414	30.782	39.620
			32.935		21.944
5	40.770	-40.674	-32.935	52.763	61.607

bzy/cm
2/3

			-48.414		43.931
6	40.770	40.674	48.414	52.769	61.607
			32.935		43.931
7	40.770	-40.674	-32.935	74.761	83.599
			-48.414		65.923
8	40.770	40.674	48.414	74.761	83.599
			32.935		65.923
9	40.770	40.674	48.414	-74.761	-65.923
			32.935		-83.599
10	40.770	-40.674	-32.935	-74.761	-65.923
			-48.414		-83.599
11	40.770	40.674	48.414	-52.769	-43.931
			32.935		-61.607
12	40.770	-40.674	-32.935	-52.769	-43.931
			-48.414		-61.607
13	40.770	40.674	48.414	-30.782	-21.944
			32.935		-39.620
14	40.770	-40.674	-32.935	-30.782	-21.944
			-48.414		-39.620
15	40.770	40.674	48.414	-8.804	.034
			32.935		-17.642
16	40.770	-40.674	-32.935	-8.804	.034
			-48.414		-17.642

At target plane distance (Zv) = 8.10 m(from neutralizer entrance)
Target plane is dump exit
Beam envelope for the given skim angles

Seg no	Horiz xovr distance Zb-m	x-centrln cm	x-env l/r cm	y-centrln cm	y-env t/b cm
1	40.770	-37.149	-26.961	-2.428	9.944
			-47.338		-14.799
2	40.770	37.149	47.338	-2.428	9.944
			26.961		-14.799
3	40.770	-37.149	-26.961	19.542	31.914
			-47.338		7.170
4	40.770	37.149	47.338	19.542	31.914
			26.961		7.170
5	40.770	-37.149	-26.961	41.534	53.906
			-47.338		29.162
6	40.770	37.149	47.338	41.534	53.906
			26.961		29.162
7	40.770	-37.149	-26.961	63.527	75.899
			-47.338		51.155
8	40.770	37.149	47.338	63.527	75.899
			26.961		51.155
9	40.770	37.149	47.338	-63.527	-51.155
			26.961		-75.899
10	40.770	-37.149	-26.961	-63.527	-51.155
			-47.338		-75.899
11	40.770	37.149	47.338	-41.534	-29.162
			26.961		-53.906
12	40.770	-37.149	-26.961	-41.534	-29.162
			-47.338		-53.906
13	40.770	37.149	47.338	-19.542	-7.170

b24/cm
3/3

			26.961		-31.914
14	40.770	-37.149	-26.961	-19.542	-7.170
			-47.338		-31.914
15	40.770	37.149	47.338	2.428	14.799
			26.961		-9.944
16	40.770	-37.149	-26.961	2.428	14.799
			-47.338		-9.944

At target plane distance (Zv) = 11.00 m(from neutralizer entrance)
Target plane is module isolation valve
Beam envelope for the given skim angles

Seg no	Horiz xovr distance Zb-m	x-centrln cm	x-env l/r cm	y-centrln cm	y-env t/b cm
1	40.770	-33.852	-21.372	-12.935	2.743
			-46.332		-28.613
2	40.770	33.852	46.332	-12.935	2.743
			21.372		-28.613
3	40.770	-33.852	-21.372	9.028	24.706
			-46.332		-6.650
4	40.770	33.852	46.332	9.028	24.706
			21.372		-6.650
5	40.770	-33.852	-21.372	31.023	46.701
			-46.332		15.345
6	40.770	33.852	46.332	31.023	46.701
			21.372		15.345
7	40.770	-33.852	-21.372	53.017	68.695
			-46.332		37.339
8	40.770	33.852	46.332	53.017	68.695
			21.372		37.339
9	40.770	33.852	46.332	-53.017	-37.339
			21.372		-68.695
10	40.770	-33.852	-21.372	-53.017	-37.339
			-46.332		-68.695
11	40.770	33.852	46.332	-31.023	-15.345
			21.372		-46.701
12	40.770	-33.852	-21.372	-31.023	-15.345
			-46.332		-46.701
13	40.770	33.852	46.332	-9.028	6.650
			21.372		-24.706
14	40.770	-33.852	-21.372	-9.028	6.650
			-46.332		-24.706
15	40.770	33.852	46.332	12.935	28.613
			21.372		-2.743
16	40.770	-33.852	-21.372	12.935	28.613
			-46.332		-2.743

beamc

FILE: b3ax/cm PEAKED PROFILE

BEAM ENVELOPE

b3ay/cm

1/3

title: iter 1.3mev/1A/4 bmlts/segment 10MW/mod peaked, one module 5/09/90

file: iter/b3ay/cm

Beam cluster centerline tangent radius Ro	=	6.200 m
Beam energy	=	1.300 MeV
Beam power per channel delivered	=	.640 MW
Total beam power delivered	=	10.240 MW for 16 channels
Beamlet width at accelerator exit	=	7.580 cm

SEGMENT SIZE AND LOCATION (Accelerator exit)

Segment No	Height 2*Bcm cm	Dist to segmnt Center x-dir Ecm cm	y-dir Dcm cm	Aiming Radius Raim m	Dist-h Zaim m	Dist-v Za m
1	6.28	46.36	26.90	6.20	40.77	20.44
2	6.28	-46.36	26.90	6.20	40.77	20.44
3	6.28	46.36	48.90	6.20	40.77	37.15
4	6.28	-46.36	48.90	6.20	40.77	37.15
5	6.28	46.36	70.90	6.20	40.77	53.85
6	6.28	-46.36	70.90	6.20	40.77	53.85
7	6.28	46.36	92.90	6.20	40.77	70.56
8	6.28	-46.36	92.90	6.20	40.77	70.56
9	6.28	-46.36	-92.90	6.20	40.77	70.56
10	6.28	46.36	-92.90	6.20	40.77	70.56
11	6.28	-46.36	-70.90	6.20	40.77	53.85
12	6.28	46.36	-70.90	6.20	40.77	53.85
13	6.28	-46.36	-48.90	6.20	40.77	37.15
14	6.28	46.36	-48.90	6.20	40.77	37.15
15	6.28	-46.36	-26.90	6.20	40.77	20.44
16	6.28	46.36	-26.90	6.20	40.77	20.44

Skim half angles x-dir = .0079 rad y-dir = .0114 rad

At target plane distance (Zv) = 5.00 m(from neutralizer entrance)
Target plane is neutralizer exit
Beam envelope for the given skim angles

Seg no	Horiz movr distance Zh-m	x-centrln cm	x-env l/r cm	y-centrln cm	y-env t/b cm
1	40.770	-40.674	-32.935	20.320	29.159
			-48.414		11.480
2	40.770	40.674	48.414	20.320	29.159
			32.935		11.480
3	40.770	-40.674	-32.935	42.319	51.158
			-48.414		33.479
4	40.770	40.674	48.414	42.319	51.158
			32.935		33.479
5	40.770	-40.674	-32.935	64.317	73.157

b3ay/cm

2/3

			-48.414		55.477
6	40.770	40.674	48.414	64.317	73.157
			32.935		55.477
7	40.770	-40.674	-32.935	86.317	95.157
			-48.414		77.477
8	40.770	40.674	48.414	86.317	95.157
			32.935		77.477
9	40.770	40.674	48.414	-86.317	-77.477
			32.935		-95.157
10	40.770	-40.674	-32.935	-86.317	-77.477
			-48.414		-95.157
11	40.770	40.674	48.414	-64.317	-55.477
			32.935		-73.157
12	40.770	-40.674	-32.935	-64.317	-55.477
			-48.414		-73.157
13	40.770	40.674	48.414	-42.319	-33.479
			32.935		-51.158
14	40.770	-40.674	-32.935	-42.319	-33.479
			-48.414		-51.158
15	40.770	40.674	48.414	-20.320	-11.480
			32.935		-29.159
16	40.770	-40.674	-32.935	-20.320	-11.480
			-48.414		-29.159

At target plane distance (Zv) = 8.10 m(from neutralizer entrance)
Target plane is dump exit
Beam envelope for the given skim angles

Seg no	Horiz xovr distance Zb-m	x-centrln cm	x-env l/r cm	y-centrln cm	y-env t/b cm
1	40.770	-37.149	-26.961	16.240	28.614
			-47.338		3.866
2	40.770	37.149	47.338	16.240	28.614
			26.961		3.866
3	40.770	-37.149	-26.961	38.238	50.612
			-47.338		25.864
4	40.770	37.149	47.338	38.238	50.612
			26.961		25.864
5	40.770	-37.149	-26.961	60.235	72.609
			-47.338		47.862
6	40.770	37.149	47.338	60.235	72.609
			26.961		47.862
7	40.770	-37.149	-26.961	82.235	94.609
			-47.338		69.862
8	40.770	37.149	47.338	82.235	94.609
			26.961		69.862
9	40.770	37.149	47.338	-82.235	-69.862
			26.961		-94.609
10	40.770	-37.149	-26.961	-82.235	-69.862
			-47.338		-94.609
11	40.770	37.149	47.338	-60.235	-47.362
			26.961		-72.609
12	40.770	-37.149	-26.961	-60.235	-47.362
			-47.338		-72.609
13	40.770	37.149	47.338	-38.238	-25.364

b3ay/cm
3/3

			26.961		-50.612
14	40.770	-37.149	-26.961 -47.338	-38.238	-25.864 -50.612
15	40.770	37.149	47.338 26.961	-16.240	-3.866 -28.614
16	40.770	-37.149	-26.961 -47.338	-16.240	-3.866 -28.614

At target plane distance (Zv) = 11.00 m(from neutralizer entrance)
Target plane is module isolation valve
Beam envelope for the given skim angles

Seg no	Horiz xovr distance Zb-m	x-centrln cm	x-env l/r cm	y-centrln cm	y-env t/b cm
1	40.770	-33.852	-21.372 -46.332	12.423	28.103 -3.256
2	40.770	33.852	46.332 21.372	12.423	28.103 -3.256
3	40.770	-33.852	-21.372 -46.332	34.421	50.101 18.741
4	40.770	33.852	46.332 21.372	34.421	50.101 18.741
5	40.770	-33.852	-21.372 -46.332	56.417	72.097 40.737
6	40.770	33.852	46.332 21.372	56.417	72.097 40.737
7	40.770	-33.852	-21.372 -46.332	78.417	94.097 62.738
8	40.770	33.852	46.332 21.372	78.417	94.097 62.738
9	40.770	33.852	46.332 21.372	-78.417	-62.738 -94.097
10	40.770	-33.852	-21.372 -46.332	-78.417	-62.738 -94.097
11	40.770	33.852	46.332 21.372	-56.417	-40.737 -72.097
12	40.770	-33.852	-21.372 -46.332	-56.417	-40.737 -72.097
13	40.770	33.852	46.332 21.372	-34.421	-18.741 -50.101
14	40.770	-33.852	-21.372 -46.332	-34.421	-18.741 -50.101
15	40.770	33.852	46.332 21.372	-12.423	3.256 -28.103
16	40.770	-33.852	-21.372 -46.332	-12.423	3.256 -28.103

Lawrence Berkeley Laboratory
1 Cyclotron Road Berkeley, California 94720
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COVER SHEET

DATE: 8-10-90

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B-29-25

ATTACHED IS THE RESULTS OF THE GAS FLOW CALCULATIONS. ADDITIONAL DETAILS & THE REPORTS FROM THE JULY GARCHING WORKSHOP WERE MAILED ON 8-10-90

FROM:

PETER PURGALIS

NUMBER OF PAGES 1 (PLUS COVER SHEET)

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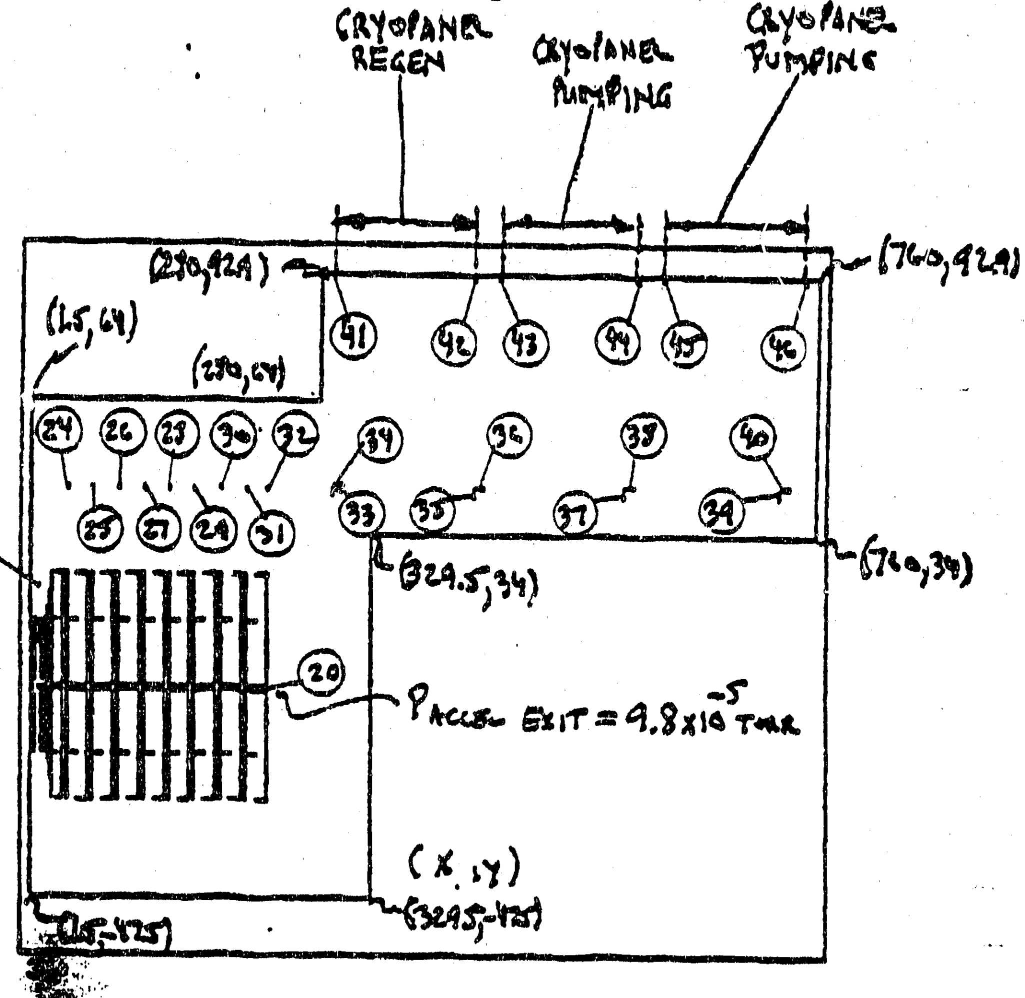
P. PURGALIS 8/9/90
2D MONTE MODEL
INPUT FILE ES01A2

1/4

$A_{TOTAL} = (W+25)(H+25)$

$A = W \times H$

W = 135 cm, H = 235 cm – PUMPING SURFACE (CHEVRON)



A = 3.1725

$P_{SOURCE} = 1.5\,mT$

$P_{ACCEL\ EXIT} = 9.8 \times 10^{-5}$ TORR

$Q = P_r\, C_0\, A\, \Delta P$

$P_r = 0.68$

$C_0 = 3.64\sqrt{\frac{T}{M}}\ \frac{\ell}{s\,cm^2} = 31\ \frac{\ell}{s\,cm^2}$ FOR D_2 @ 293 K

$A = 1.56\,cm \times 258\,cm = 402\,cm^2$

$Q = .68\left(31\ \frac{\ell}{s\,cm^2}\right)(402\,cm^2)(1.5 \times 10^{-3}) = 12.8$ TORR $\frac{\ell}{s}$

ONE MODULE HAS TWO ACCELERATOR ARRAYS

SO $Q = 12.8 \times 2 = \boxed{25.6 \text{ TORR-}\frac{\ell}{s} \text{ FOR EACH MODULE}}$

END

DATE FILMED

02 / 07 / 91